Evaluation of Optical Instruments for Real-Time Continuous Monitoring of Smoke Particulates

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—*Instruments pictured on the cover (left to right):
BGI PQ200, Met One GT-640, Andersen aethalometer,
Radiance Research nephelometer, and the MIE DataRam.*

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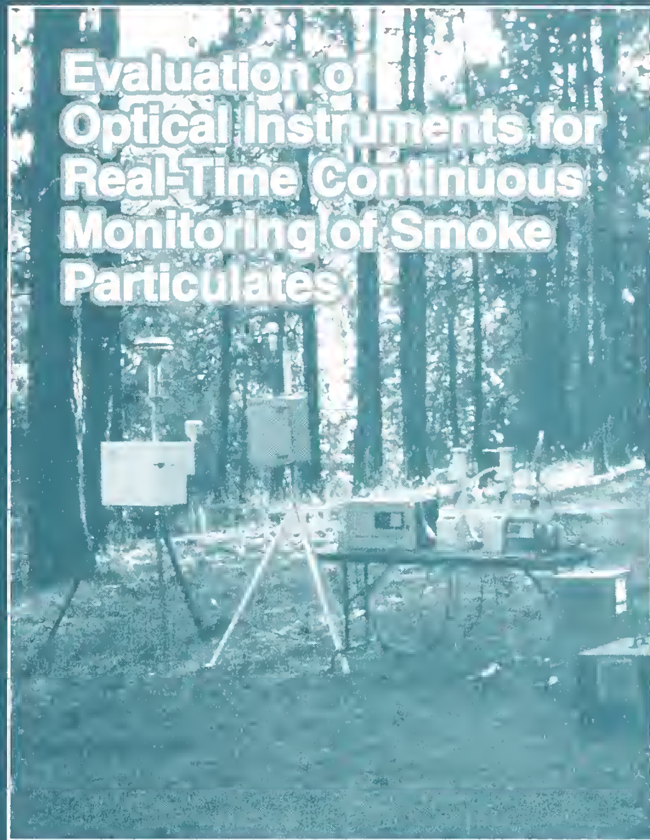

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9E92F52—$PM_{2.5}$ Air Sampler

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Executive Summary

The USDA Forest Service, Missoula Technology and Development Center (MTDC) is evaluating commercially available optical instruments that measure particulate concentrations in real time. Forest and fire managers and air-quality specialists need such information when smoke particulates from burning biomass generate air-quality concerns. Airborne particulates, especially particles smaller than 2.5 μm in diameter ($PM_{2.5}$), pose potential health, visibility, safety, and nuisance problems. Measuring these airborne particulate concentrations is very important to land managers as they use prescribed fire in forests and rangelands.

The key items of MTDC's evaluation are accuracy in measuring or estimating smoke concentrations, comparison of results from identical instruments (instrument comparison), reliability, operational characteristics such as portability, power requirements, data collection, and cost. The data were collected in the laboratory and in a field setting.

The five brands of optical real-time instruments we evaluated had few fundamental differences. Accurately estimating ambient particle concentrations based on their light-scattering and absorption properties is difficult. Many variables affect the optical characteristics of particles, increasing the difficulty real-time instruments have in accurately estimating the mass concentration of particulate. However, optical instruments can estimate the direction of change in the concentration of particulates and the magnitude of the overall ambient particulate concentration.

Introduction

Measuring airborne particulate concentrations is very important to land managers as managed forest and rangeland burning increases. Airborne particulates, especially particles smaller than 2.5 μm in diameter ($PM_{2.5}$), pose potential health, visibility, safety, and nuisance problems. Managing smoke to protect human health and public welfare is an essential part of each prescribed burn plan. The proper use of ambient air monitoring can help ensure that wildland burning complies with State and Federal air-quality laws and regulations while satisfying land management objectives.

Two common types of instruments that measure particle concentration use gravimetric or optical techniques. Gravimetric instruments collect particulates on ventilated filters. The filters are processed at special laboratory facilities to determine the mass concentration of particulate. Optical instruments can use light-scattering or light-absorbing principles to estimate the mass concentrations of airborne particulates. Optical instruments offer several advantages, including real-time, mass-concentration estimates, portability, low power consumption, and relatively low cost. This study focused on evaluating optical instruments alongside a Federal Reference Method (FRM) gravimetric device.

Several commercial vendors manufacture real-time particulate monitoring instruments for estimating airborne mass concentrations. MTDC has evaluated several monitors to identify the strengths and weaknesses of each instrument for settings where air quality is primarily influenced by smoke from biomass burning. The key items evaluated were:

- Accuracy in measuring or estimating smoke concentrations.
- Comparison of results from identical instruments (instrument comparison).
- Reliability.
- Operational characteristics such as portability, power requirements, data collection, and cost. The data were collected in the laboratory and in field settings.

This evaluation will provide forest and fire managers, and air-quality specialists, with information on a variety of commercially available real-time particulate monitors for settings where air quality is primarily influenced by smoke particulates. This information is expected to be useful in smoke management. This evaluation does not recommend one instrument over another, nor does it verify the optical characteristics of any instruments.

Background

A comprehensive smoke management plan is essential for the successful use of fire as a wildland management tool. Monitoring ambient air to ensure that smoke does not threaten people or protected areas is an essential element of such a plan. The demands on a particle measurement device in a wildland fire situation are severe.

Ideally, the instrument should be portable (not require line power), be rugged, (it will be transported in remote areas), be easy to set up and operate by one person, retrieve data in useful forms, and have known accuracy even at low particulate concentrations where smoke would be just a nuisance.

The estimated mass concentrations from real-time instruments can be used for a variety of purposes. Real-time smoke concentration data can be used by the Forest Service to help manage a fire and its production of smoke. The data may also be used to anticipate public notification needs as well as to verify the smoke concentration that actually occurs for regulatory purposes. In the future, real-time smoke data may be used with smoke models to produce more accurate predictions of smoke concentrations.

Gravimetric or filter-based monitoring techniques have been used for years to quantify mass concentration levels of airborne particulate matter. Filter-based sampling is labor intensive. Filters must be conditioned, weighed before sampling, installed and removed from the instrument, and reconditioned and weighed again at special facilities. Results from the weighing may not be available for days or weeks, depending on the workload at the laboratory. Also, airflow rates and elapsed sampling time must be carefully monitored and recorded to ensure accurate results. Filter-based techniques integrate samples over a long period of time, usually 24 h (depending on the exposure), to obtain the required minimum mass for analysis. Filter-based techniques can have inaccuracies in both mass and composition due to the loss of volatile and semivolatile components. The components can be lost during collection or after collection but before the filter has been analyzed.

Optical, real-time, continuous particulate monitoring instruments do not have many of the problems associated with the gravimetric technique. Optical instruments do not require that filters be weighed. They provide concentration estimates that can be released immediately to land managers and the public. Many of these instruments are portable. They can be sited in the areas of greatest interest, usually downwind of burns.

Evaluation Criteria

The evaluation criteria for the study are designed to look at the overall use of the optical instrument, its accuracy, comparisons among instruments, and cost. In future field applications, the instruments will probably be used by field technicians at various locations throughout the burning season. Portability, ease of set up, ease of data collection, and ease of data manipulation are extremely important. Other considerations a smoke manager should consider when deciding which instrument is most appropriate for each application include: power consumption, calibration requirements, reliability, and similar factors. The list of criteria developed for the evaluation includes:

Suitability—The instrument should be able to estimate particulate concentrations generated from smoke at the nuisance level, continuously and in real time. The instrument should be portable, operate on low power, (preferably batteries), be housed in a weatherproof enclosure, and be affordable for a National Forest.

Ease of Use—The instrument should be easy to operate and set up. Data collection and manipulation should be straightforward. Calibration should be simple.

Reliability—The instrument should be reliable and have strong manufacturer support.

Accuracy and Instrument Comparison—Accuracy is based on each instrument's real-time mass concentration estimates compared to a gravimetric standard. Estimates from identical instruments were compared to each other. The instruments should be reasonably stable so that accuracy or precision does not vary markedly for a given instrument.

Instruments

Two basic types of instruments were used in the evaluation: optical real-time continuous particulate monitors and gravimetric instruments. Tables 1 and 2 summarize the specifications and accessories for the real-time instruments.

Optical Real-Time, Continuous Particulate Monitors

The optical real-time, continuous particulate monitors used in the evaluation may be classified into two types: predominantly light-scattering instruments and predominantly light-absorbing instruments. Light-*scattering* instruments, called nephelometers, measure the amount of light scattered over a known path length and then use a mathematical relationship to estimate the aerosol mass concentration. The particle light scattering (b_{sp}) value is determined by illuminating particles, individually or as a group, and measuring the scattered intensity at different orientations from an incident light source. The orientation of the light source to the particles and receiver will determine whether the instrument is primarily back scattering, forward scattering, or total integrating.

Light-*absorbing* instruments, called aethalometers, quantify the light-absorbing aerosol (black carbon, for example) by depositing the aerosol on a quartz-fiber filter and measuring the light transmission or reflectivity. Aethalometers also compute measured light attenuation due to black carbon.

Light-Scattering Instruments

The Met One Model GT-640 particulate monitor (figure 1) is a complete ambient air sampler using a forward light-scattering detector and built-in data logger. A laser optical sensor detects and measures particulate concentrations up to 10,000 $\mu g/m^3$. Built-in calibration functions are included. The unit has an internal relative humidity sensor that turns on an inlet heater at 55-percent relative humidity. The monitor can be configured with either a PM_{10} (particulate matter finer than 10 μm) or $PM_{2.5}$ (particulate matter finer than 2.5 μm) cutoff inlet. Total suspended particulate concentrations can be estimated by removing the cutoff device. Data are digitally recorded and stored with time and date information. Stored data are retrieved through an RS-232 port connected to a laptop computer or

Table 1—Specifications of the real-time, continuous, particulate-monitoring instruments evaluated.

	Price (dollars)	Size (inches)	Weight (pounds)	Mass concentration range ($\mu g/m^3$)	Power requirements	Internal calibration	Internal data storage	Internal battery	Analytical filter
Met One GT-640	5,382	15.7 x 11.7 x 8	23	0 to 10,000	12 V dc, 1 A	X	X		
MIE DataRam	11,000	5.28 x 7.25 x 13.63	11.7	0 to 400,000	6 V dc, 3 A	X	X	X	X
Radiance Research	4,795	22 x 5 x 7	5.7	0 to 1,000	12 V dc, 1 A		X		
Optec NGN-3	12,900	10.7 x 8.2 x 16.5	27	0 to 16,666	13.8 V dc, 4.5 A	[1]X			
Andersen aethalometer	16,645	19 x 12.5 x 10.5	20	0 to 1,000	Line power, 115 V ac	X	[2]X		

[1] Requires external supply of span gas. [2] Data storage with 3.5-in floppy disk installed.

Table 2—Accessories for the real-time, continuous particulate-monitoring instruments evaluated.

	Inlet heater (standard)	$PM_{2.5}$ cutoff	Environmental enclosure ([1]standard)	Relative humidity ([2]standard)	Ambient temperature	Meteorological equipment
Met One GT-640	Standard	X	[1]Standard	[2]Standard	X	[3]X
MIE DataRam	X	X				
Radiance Research	[4]X			X	X	
Optec NGN-3	Standard	X			[5]Standard	
Andersen aethalometer		X	X			

[1] Self-contained fiberglass enclosure.
[2] Internal relative humidity sensor standard, ambient relative humidity sensor optional.
[3] Wind sensor, ambient temperature, ambient relative humidity.
[4] Continuous heater or proportional, selectable heater.
[5] Internal temperature standard, external temperature optional.

Figure 1—The Met One Instruments GT-640 particulate monitor with meteorological instrumentation.

through an external modem. The logger will record concentrations automatically along with date and time, whenever power is applied. Optional connections on the bottom of the GT-640 allow various meteorological sensors to be attached. All internal components are housed in a weatherproof enclosure. The unit can be powered by an ac or dc power source.

The DataRam (figure 2) is a compact, self-contained instrument that internally estimates mass concentration from the measured scattering of light. The instrument can measure particulate concentrations from 0.1 to 400,000 $\mu g/m^3$, according to the vendor. The instrument continuously displays the current and time-weighted average mass concentration while logging up to 10,000 data points. Data can be downloaded from the instrument through an RS-232 port. The DataRam can be configured with either a $PM_{2.5}$ or PM_{10} impactor head to prevent particles larger than 2.5 or 10 μm, respectively, from entering the optical chamber. For custom calibrations, or to analyze the chemical composition of particulates, the particulates can be collected on a 37-mm filter located in the instrument's base. An inline heater may also be installed for monitoring in humid conditions (the manufacturer suggests using the heater when the relative humidity is higher than 70 percent). The instrument's tubular heater is designed to heat the sampled air stream to evaporate liquid water from airborne particles or to eliminate fog droplets. The DataRam is powered by an internal rechargeable battery or by an external dc or ac power source. The DataRam has a built-in, internal calibration device.

Figure 2—The MIE DataRam.

The Radiance Research Portable Nephelometer, Model M903 (figure 3) is a lightweight, low-power instrument designed for portable operation as well as general environmental monitoring. The M903 measures and displays B*scat* (backscattering). It does not display a computed estimate of mass concentration as do the other nephelometers in the evaluation. Mass concentrations can be estimated from the B*scat* readings. The instrument has a particulate measurement range of approximately 1 to 1,000 $\mu g/m^3$ when mass concentration is estimated from B*scat*. The instrument has an internal data logger that will store scattering coefficient averages and the operating parameters that are used to estimate the B*scat*. The stored data can be retrieved using a personal computer through an RS-232 port. Different averaging times and log intervals may be set. The instrument can store approximately 2 weeks of 5-minute averages. A source of a gas, such as Freon, is required for calibration. The unit can be powered by an ac or dc power source.

Figure 3—The Radiance Research nephelometer, Model M903, with an attached inlet heater.

The Optec NGN-3 $PM_{2.5}$ size-cut nephelometer (figure 4) is a self-contained instrument developed to estimate $PM_{2.5}$ aerosol scattering and mass concentrations. The NGN-3 is based on the Optec NGN-2 ambient nephelometer that is used by the IMPROVE program for visibility studies and in other applications. The NGN-3 integrates the optical design of the NGN-2 ambient nephelometer with both a $PM_{2.5}$ size-cut separator and an inline sample heater to measure the dry scattering fraction of extinction by fine-mass aerosols. Once measured, the B*scat* is converted to mass concentration using a region-specific, user-selected empirical conversion factor. The NGN-3 continuously outputs both B*scat* and a fine-mass concentration estimate with a minimum integration time of 2 minutes. The NGN-3 has ***no*** internal data storage capabilities, outputting data in serial or analog form. Portable remote monitoring data loggers such as the Campbell

Figure 4—The Optec NGN-3 $PM_{2.5}$ size-cut nephelometer.

Scientific CR-23X or a laptop computer are needed for data storage.

The NGN-3 draws ambient air through a sample inlet line. An SKC spiral inlet mounted at the sample air inlet removes coarse particulates from the sample stream. The sample air is heated (to lower the relative humidity) as it enters the nephelometer. The temperature of the heated air is output continuously. To ensure monitoring accuracy, the instrument performs automatic zero calibrations at user-defined intervals. Manual zero and span calibration checks may be performed at any time. An external span gas such as Freon is required for calibration. The NGN-3 can be powered by either an ac or dc power source.

Light-Absorbing Instruments

The Andersen RTAA 800 aethalometer (figure 5) collects “elemental” or “black” carbon (BC) on a quartz fiber tape, measuring the optical absorption continuously while the spot of aerosol accumulates. The optical absorption estimations are converted to estimate the mass concentration of BC in $\mu g/m^3$. A display on the front of the instrument shows the calculated BC concentration. A keypad allows the user to interact with the embedded computer. Data is automatically stored on an internal floppy disk. The instrument also has an RS-232 port and an analog output. The instrument can be configured with a particulate-size cutoff device for selective measurements. The instrument runs on 110 V ac.

Gravimetric-Based Instruments

Gravimetric-based instruments were used in the evaluation to compare their results to those of the real-time samplers. Gravimetric- or filter-based instruments work by drawing air at a controlled rate through a filter that collects the fine particulate matter. The filter is carefully weighed at a special facility before and after sampling the air. This method provides very accurate results of the quantity of particulate that was collected during the test period. The particulate mass value is divided by the total volume of air drawn through the filter, yielding the average mass concentration for the test period, typically in $\mu g/m^3$. The gravimetric instruments can be configured with impactor or cyclone size-selector devices to remove large particles. Three different gravimetric instruments were used in the evaluation; two Federal Reference Method $PM_{2.5}$ air samplers and a $PM_{2.5}$ sampler developed by the Rocky Mountain Research Station’s Fire Sciences Laboratory (Fire Sciences Laboratory) in Missoula, MT.

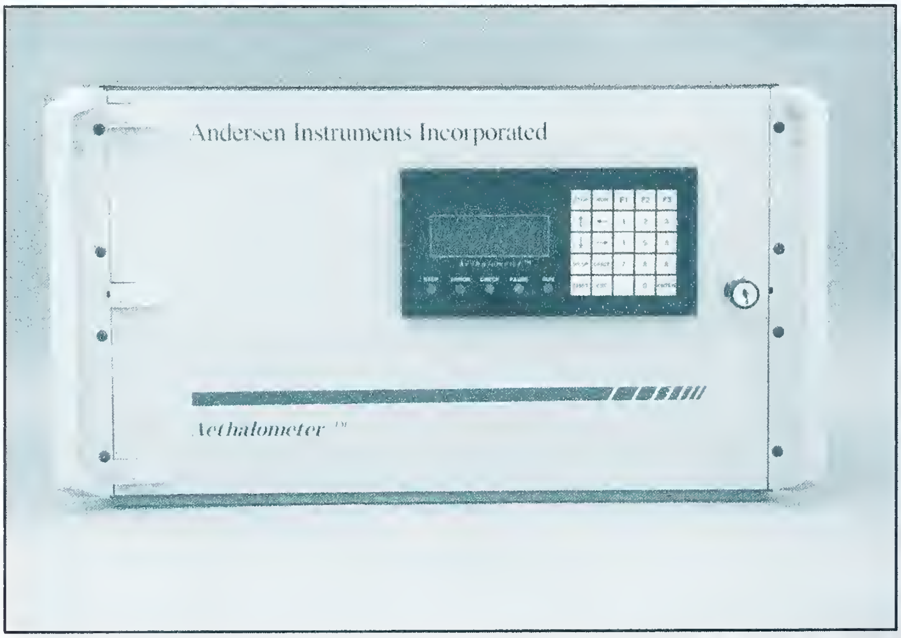

Figure 5—The Andersen Instruments RTAA 800 aethalometer.

Federal Reference Method (FRM) $PM_{2.5}$ Air Samplers

Two different manufacturers of FRM $PM_{2.5}$ samplers were used in the evaluation: the BGI, Inc., PQ200 (figure 6) and the Partisol FRM Model 2000 manufactured by Rupprecht and Patachnick (R&P). They both have similar design, performance characteristics, and operational requirements. Both are microprocessor-controlled, volumetric flow rate air-sampling instruments that obtain a valid $PM_{2.5}$ air sample. The particulates are collected on 47-mm Teflon membrane at a volumetric sample rate of 16.67 L/min after being size discriminated through two inertial separators designed by the U.S. Environmental Protection Agency.

Ambient temperature and barometric pressure measurements are made at actual sample conditions. A microprocessor and volumetric flow control system are integrated to maintain sampling parameters while sampling data are continuously logged into the processor memory. Memory stores 5-minute actual ambient temperature and pressure conditions along with volumetric sample flow rate, filter temperature, and pressure. The operator recovers measured values and flags indicating anomalies by downloading the summary to a laptop computer. The instruments may be powered by an internal battery, by external batteries, or by solar power.

Figure 6—The BGI PQ200 Federal Reference Method $PM_{2.5}$ sampler.

Filters collected by the BGI PQ 200 were weighed at the Montana Department of Public Health and Human Services Environmental Laboratory in Helena, MT. Filters collected by the R&P Partisol Model 2000 sampler were weighed at IML Air Science in Sheridan, WY.

Fire Sciences Laboratory $PM_{2.5}$ Air Sampler

This gravimetric instrument was developed by the Fire Sciences Laboratory for conducting airborne smoke studies. The instrument uses a computer-controlled volumetric airflow controller to draw air over a 37-mm Teflon filter at a rate of 28.8 L/min. The air is first drawn through a size-selected cyclone device to remove particulate larger than 2.5 μm. The filters were weighed in a special environmentally controlled facility located at the Fire Sciences Laboratory.

Test Methods and Descriptions

Tests were conducted in three phases: 1998 laboratory tests, field tests conducted in the fall of 1998 and 1999, and laboratory tests conducted in the spring of 2000. While the primary focus of these tests was to determine the accuracy and to compare the results from several identical instruments, operational and reliability characteristics were also being evaluated.

Laboratory Tests During 1998

Objectives—The objectives of the 1998 laboratory tests were to determine whether the optical and gravimetric instruments showed significant differences when measuring smoke particles produced from burning biomass under controlled conditions. If possible, we hoped to determine a correction curve for the optical instruments. A report on these tests, *Laboratory Evaluation of Two Optical Instruments for Real-Time Particulate Monitoring of Smoke* (9925-2806-MTDC, figure 7), was published in 1999.

Location—The laboratory tests were conducted at the Fire Sciences Laboratory's large (131,000 ft^3) combustion chamber. The instruments were placed side by side and operated on a platform 55 ft above the chamber floor (figure 8).

Instruments—Two optical instruments were evaluated in the 1998 laboratory tests, the MIE DataRam and the Radiance Research nephelometer. The MIE DataRam was configured with a $PM_{2.5}$

Figure 7—A report (9925-2806-MTDC) was published in 1999 detailing the laboratory evaluation of two real-time particulate moniotrs.

cutoff device and inlet heater. The Radiance Research nephelometer measured total suspended particulate. Two different gravimetric devices were used, an FRM $PM_{2.5}$ sampler manufactured by Rupprecht and Patachnick and a $PM_{2.5}$ sampler developed by the Fire Sciences Laboratory for airborne smoke studies. The FRM was available only for a few tests. The Fire Sciences Laboratory's gravimetric sampler was used for all tests.

Test Descriptions—The experiments were conducted at ambient conditions inside the closed chamber at temperatures of 70 to 90 °F and 30- to 50-percent relative humidity. Small beds of flaming and smoldering ponderosa-pine needles on the chamber floor generated the smoke for most of the tests (figure 9). Several tests were conducted using smoke generated from burning duff. A total of 66 tests were conducted. The duration for each test varied depending on the estimated particulate concentration. Higher concentration tests were shortened to prevent clogging the filters. Lower concentration tests took longer to accumulate enough mass on the filters for accurate weighing. The average test took about an hour.

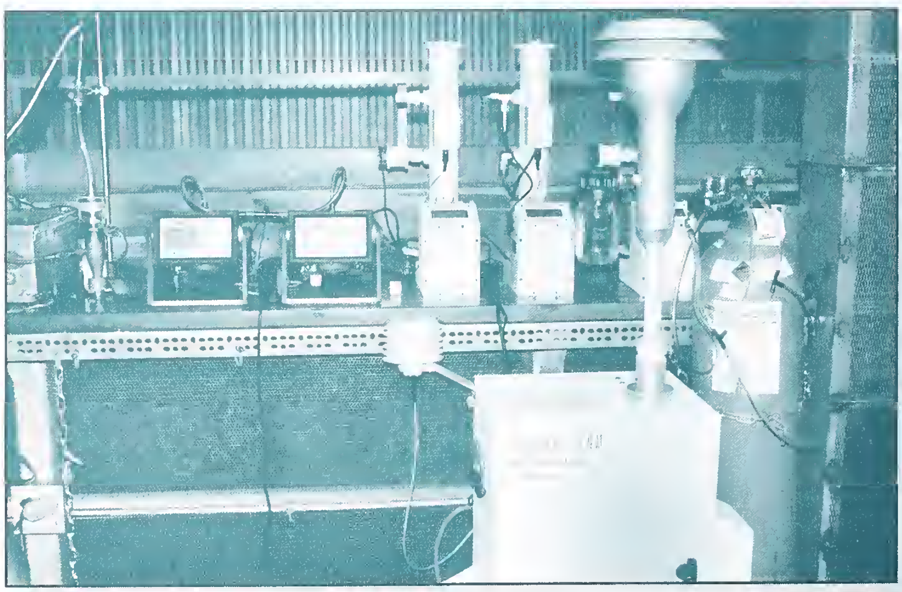

Figure 8—Instrument layout on the smoke-sampling platform in the combustion chamber.

Figure 9—An example of the fire beds of pine needles used to produce smoke in the laboratory combustion chamber.

Field Tests During 1998 and 1999

Objectives—The objectives of the field tests were to validate the 1998 laboratory results by comparing results from the optical instruments to those from a gravimetric instrument in a field environment. The instruments were placed side by side downwind of prescribed burns or wildland fires to gather data from the smoke (figure 10). The field tests also gave us the opportunity to obtain field experience with each of the instruments.

Location—The field tests were conducted near prescribed and wildland fires in and around the Missoula and Bitterroot Valleys in Montana and northern Idaho. The distance from the burn to the instruments varied, depending on the availability of secure land where the instruments could be set up. Because the instruments were set up in relatively pristine airsheds, elevated particulate levels were assumed to be from smoke.

Instruments—Only the DataRam and Radiance Research nephelometer were available for the field tests conducted in 1998. The Fire Sciences Laboratory's gravimetric instrument was used for gravimetric comparisons. The Met One GT-640 and the Andersen aethalometer were also available for the 1999 Field tests. The BGI PQ200 was used as the gravimetric standard for all the 1999 field tests.

Test Descriptions—The instruments were typically placed side by side and left overnight where it appeared residual smoke from the burns would settle. All instruments were equipped with their respective $PM_{2.5}$ cutoff inlets and inlet heaters. Temperature, relative humidities, and wind all varied from test to test. The instruments were powered by a Honda 1,000-W portable generator modified to operate for extended periods of time.

Laboratory Tests During 2000

Objectives—The 2000 laboratory tests had several objectives. One objective was to conduct tests similar to the 1998 laboratory tests on several new instruments to compare their performance to the other instruments. The new instruments included the Met One GT-640, the Optec NGN-3 nephelometer, and the Andersen aethalometer. Another objective was to obtain samples at lower concentrations of particulate (under 150 $\mu g/m^3$) than were measured during

Figure 10—Instrument layout during the 1999 field tests.

the previous laboratory tests. We also conducted several tests at high relative humidities (above 70 percent) to determine the effectiveness of the inlet heaters. Finally, we compared gravimetric samplers.

Location—The 2000 laboratory tests were conducted at the Fire Sciences Laboratory's smoke chamber. The instruments were placed side by side on a platform 55 ft above the chamber floor.

Instruments—The instruments included in the 2000 laboratory tests were:

- Two MIE DataRam instruments.
- Two Radiance Research nephelometers.
- Two Met One GT-640's.
- One Optec NGN-3 nephelometer.
- An Andersen aethalometer.
- Two BGI PQ200's.
- A Fire Sciences Laboratory $PM_{2.5}$ gravimetric sampler.

A total of 11 instruments and seven different makes or models were tested. All instruments were configured with their respective $PM_{2.5}$ cutoff inlet and inlet heater. To maintain consistency with the previous laboratory and field tests, the Radiance Research nephelometer was configured to estimate total suspended particulate.

Test Descriptions—Except for the high-humidity tests, all the experiments were conducted at ambient conditions inside the closed chamber. Again, very small beds of dry ponderosa-pine needles (weighing from 50 to 150 g) were burned to generate the smoke. These beds were much smaller than in the 1998 tests where we burned more needles to generate higher particulate levels.

A number of tests were conducted to evaluate the performance of identical instruments, specifically the MIE DataRam, the Radiance Research nephelometers, the Met One GT-640's, and the FRM samplers. We not only determined the accuracy of each real-time instrument compared to the gravimetric instrument, but we also compared each of the instruments to another like it.

High-humidity tests were performed between similar instruments with and without their respective inlet heaters.

Evaluation Results and Discussion

Results of the evaluation are broken down into the respective criteria as detailed in the *Evaluation Criteria* section. Table 3 summarizes suitability, ease of use, and reliability results. Other than the statistical results for accuracy and comparison of identical instruments to each other, evaluation results are subjective, based on the authors' operational experience with the instruments and their opinions.

Suitability

Mass Concentration Range—All of the continuous, real-time instruments evaluated can estimate mass concentration levels from 1,000 $\mu g/m^3$ and lower.

Portability—The MIE DataRam was the smallest and most portable of all the instruments, although none is really heavy or bulky. The DataRam comes with its own protective carrying case that measures 11 x 12 x 16 in. The Radiance Research nephelometer is lightweight, a little larger than the DataRam, and does not come with a carrying case. The other instruments are larger, heavier, and more cumbersome than the DataRam and Radiance nephelometer. One person can carry any one of the instruments without a problem.

Power Consumption—All the continuous real-time instruments are configured to run on standard 110- to 115-V ac power. Except for the Andersen aethalometer, all the instruments consume very little power and can be configured to run on 6- or 12-V batteries. The MIE DataRam is the only instrument that has an internal, 6-V, 6.5-Ah battery supplying enough power to run the instrument for at least 24 h on a full charge. The DataRam's inlet heater requires an additional battery. The DataRam can also be configured to operate on an external 6-V power source. The Radiance nephelometer can be configured to run on a 12-V battery. It consumes about 4 W of power. More power is required if the inlet heater is attached. The Met One GT-640 can be operated with a 12-V battery. It draws about 2 A. The Optec NGN-3 requires a 13.8-V dc power source providing a minimum of 5 A. A large battery recharged by a solar panel could power most of these instruments.

Weatherproof Enclosure—These instruments contain sensitive electronic components that must be protected from harsh environmental conditions, especially rain. The Met One GT-640 is the only instrument that comes standard in a weatherproof enclosure. An optional weatherproof enclosure is available for the Andersen aethalometer. The manufacturers do not supply weatherproof enclosures for the Radiance Research and Optec NGN-3 nephelometers or for the MIE DataRam.

Cost—The cost for each instrument varies depending on the accessories. The least-expensive instrument was the Radiance Research nephelometer, which costs $4,795. The Met One GT-640 costs $5,382, (including a tripod and $PM_{2.5}$ cutoff device). The MIE DataRam costs $11,005, (including the inlet heater, $PM_{2.5}$ cutoff device, and ambient air-sampler inlet). The Optec NGN-3 costs $12,900. The Andersen aethalometer costs $16,645. Consult the manufacturer for current prices.

Ease of Use

Learning Curve—Each instrument has its own peculiarities, but none is extremely difficult to learn to operate. Changing monitoring parameters such as log interval and times is easiest on the MIE DataRam and Met One GT-640. All the parameters can be modified by using the front panel keypads and following simple directions. Parameters for the Andersen aethalometer can be changed using its own keypad. A computer is needed when changing some of the operational parameters on the Radiance and Optec nephelometers.

Setup—All of the real-time continuous monitors are relatively easy to transport and set up. Once the monitors have been calibrated, all that has to be done is to take them to the desired location and turn them on. The only difficulty encountered was placing the Met One GT-640 on its tripod due to the awkward mounting brackets, the unit's weight, and the tripod's height.

Table 3—Summary of the evaluation criteria results for the real-time, continuous, particulate-monitoring instruments evaluated. Results are based on a scale of 1 to 10, with 1 being the lowest and 10 being the highest.

	Price (dollars)	Portability	Learning curve	Setup	Data collection	Data manipulation	Calibration	Reliability	Customer service
Met One GT-640	5,382	7.5	7.5	7	8.5	7.5	[1]8	9	10
MIE DataRam	11,000	10	8.5	10	9	8.5	9.5	9	10
Radiance Research	4,795	9.5	7.5	9.5	8.5	8	7.5	8.5	8
Optec NGN-3	12,900	7.5	7	9.5	7.5	8.5	8	[2]NA.	10
Andersen aethalometer	16,645	8	8	9.5	9.5	8.5	[3]NA.	[2]NA.	10

[1] Results based on model tested. Newest model has simplified calibration. [2] Insufficient data. Did not operate long enough to allow a good judgment.
[3] Received factory calibrated. Did not repeat factory calibration procedure.

Data Collection—A laptop computer using an RS-232 port and Microsoft Windows standard HyperTerminal interface was used to download the data from all of the instruments except the Optec NGN-3 and the Andersen aethalometer. A dedicated laptop using a communication package called ProComm Plus was used to log data from the Optec NGN-3. The Andersen aethalometer internally logs its data to a floppy disk.

Data Manipulation—Microsoft Excel spreadsheets were used to manipulate the data. All instruments provide mass concentration ($\mu g/m^3$) except the Radiance nephelometer, which provides B*scat*. B*scat* can readily be converted to mass concentration within Excel. The Met One outputs data with a header at 40-minute intervals. The header must be removed and data points consolidated for graphing or averaging. The DataRam outputs data every other line in the spreadsheet. When opening the file, blank lines must be eliminated before graphing or averaging. Both the Met One and the DataRam offer optional software packages to eliminate these operations.

Calibration—The DataRam and Met One use internal calibration methods. The DataRam performs its zero calibration and completes a span check when a knob on the back panel is rotated to insert the calibration rod. The LCD panel prompts the user to perform the operations. The DataRam can also be gravimetrically calibrated for a particular aerosol. The mass concentration on its 37-mm membrane filter is compared to the optically derived concentration by computing the Time Weighted Average (TWA) using the Estimated Time (ET) and flow-rate values. The Met One's internal zero and span calibration is performed by turning a knob on the instrument's side panel. Zero and span can be adjusted by using a small flat-head screwdriver and turning two screws in the side panel (the latest model of the GT-640 internally performs zero and span adjustments).

The Radiance Research nephelometer requires particle-free air (zero air or a HEPA filter) to perform the zero calibration and an external refrigerant gas, such as Freon, SF_2 or CO_2, for the span constant. The constants on the panel display must be adjusted to match the zero and span readings. The Optec NGN-3 has an internal zero air filter. An external refrigerant gas (R-134) is used to obtain the measured scattered light value for the span calibration. Achieving a stabilized calibration for these instruments can take 20 minutes or longer. The Andersen aethalometer performs its calibration internally during each startup.

Reliability

All instruments performed reliably with only minor problems. The manufacturers were prompt and helpful when needed.

MIE DataRam: The front panel keypad was not responding and was returned to the vendor and promptly fixed. The customer service was excellent.

Radiance Research: This instrument was considerably overestimating the B*scat* reading. The vendor provided directions for cleaning the optics. Cleaning brought the nephelometer back into normal operating range. The vendor would have repaired the instrument if cleaning had failed. Radiance Research is a very small company. It took several days for the company to respond to the problem although they were very helpful once they responded.

Met One: The instrument was recalled for an upgrade and returned promptly. Service was excellent.

Optec NGN-3: No problems.

Andersen Aethalometer: No problems.

Accuracy and Instrument Comparison Results

Accuracy and instrument comparison results are based on the two laboratory studies and the field tests. Accuracy was determined by comparing the average mass concentration to the gravimetric results for each test. The average mass concentration for an individual test was calculated by averaging the logged mass concentrations for the test duration. For instance, the MIE DataRam was programmed to average and log the mass concentration in 1-min intervals. For a 1-h test, the average mass concentration would be the average of the 60 logged values. The average test mass concentration for the gravimetric instruments was calculated by dividing the total accumulation of mass deposited on the filter by the total volume of air sampled. Instrument comparison results are determined by comparing the results from identical instruments.

Accuracy and instrument comparisons are broken down for each instrument. Comparison results were not available for the Optec NGN-3 and the Andersen aethalometer because only one of each instrument was available for testing.

Accuracy and instrument comparisons of each instrument type are judged by the least squares linear regression coefficients (slope and correlation coefficient R^2) obtained for the number of samples (N). The intercept was forced to be zero for clarity. Each figure will show the appropriate data points, slope equation, and the correlation coefficient. For comparison purposes, a line has been drawn at 45 degrees, indicating the best possible one-to-one relationship.

Gravimetric Instruments

The two FRM instruments compared extremely well. Figure 11 shows that the FRM samplers located beside each other during the 2000 laboratory tests had a slope of 0.99 and an R^2 value of 0.97 over a range of $PM_{2.5}$ mass concentrations of 40 to 215 $\mu g/m^3$. Results of the collocation studies of the Fire Sciences Laboratory's gravimetric sampler to the FRM during the 1998 and 2000 laboratory tests indicate that the Fire Sciences Laboratory's sampler measured about 10-percent lower than the FRM. Statistical results show a slope of 0.90 with an R^2 value of 0.93 (figure 12). Based on this comparison, all Fire Sciences Laboratory sampler results used in the real-time continuous comparison were corrected by 1.11 (1/0.90) to equalize their results with the FRM.

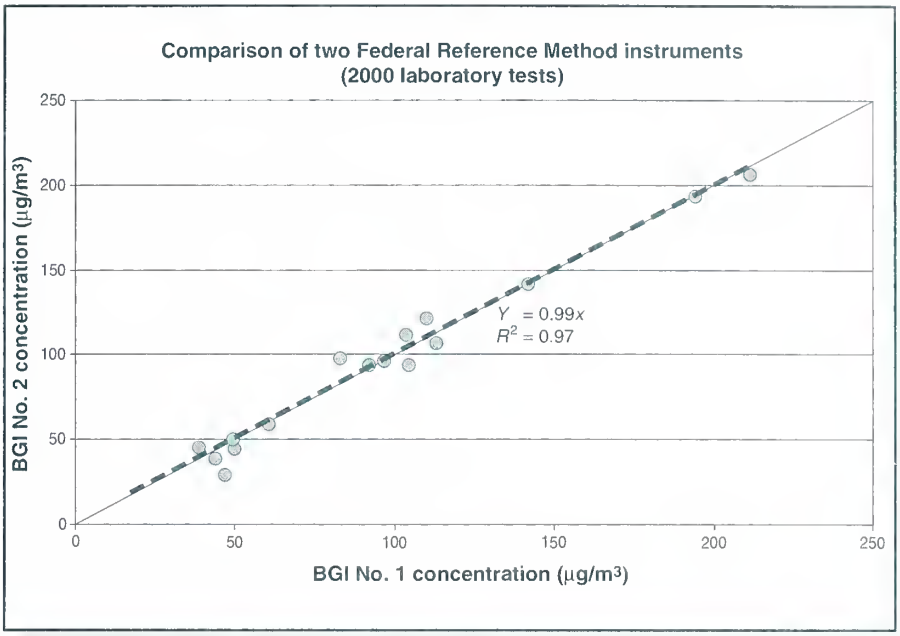

Figure 11—Comparison of the two BGI Federal Reference Method gravimetric samplers used in the 2000 laboratory tests.

Real-Time Continuous Monitoring Results

Met One GT-640

1998 Laboratory Tests—The Met One GT-640 was not available for these tests.

Field Tests—Only one GT-640 was available for the field tests. Results (figure 13) show the instrument overestimated the mass concentrations by 10 percent in the field environment (slope = 1.10 when compared to the FRM. The R^2 value was poor at 0.35 but only 12 data points were obtained.

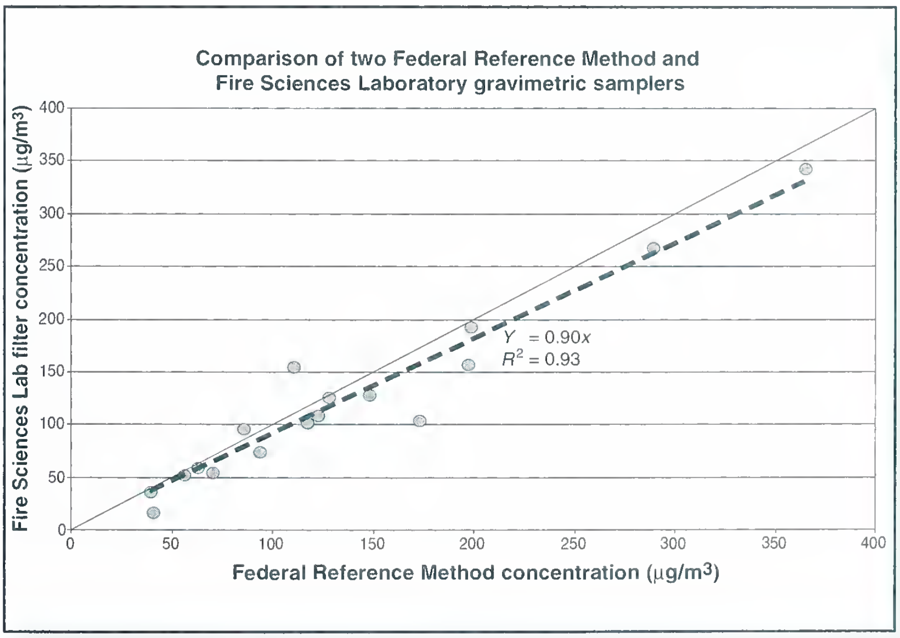

Figure 12—Regression results of the collocated Federal Reference Method and the Fire Sciences Laboratory gravimetric instrument from the 1998 and 2000 laboratory tests.

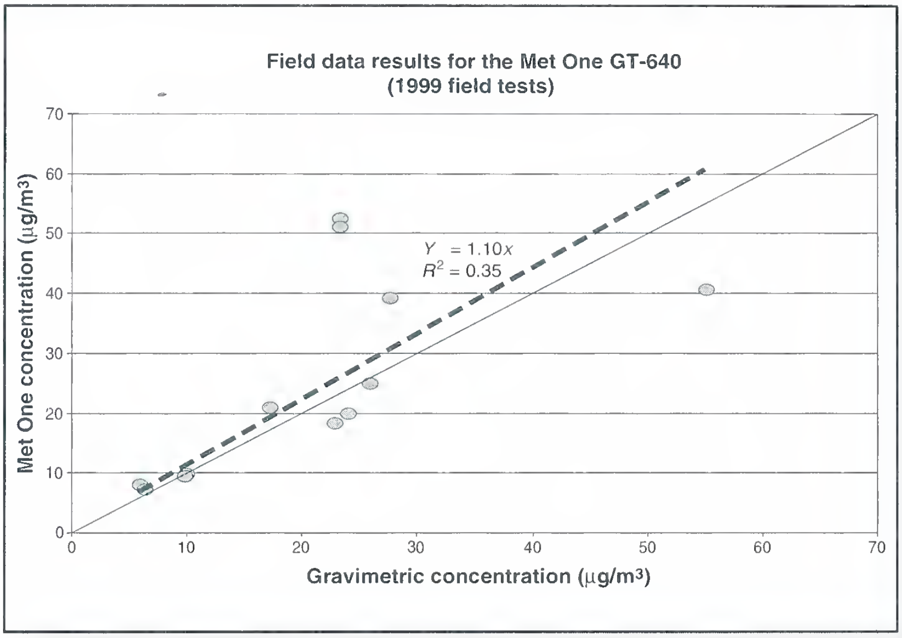

Figure 13—Comparison of the Met One GT-640 and gravimetric results from the 1999 field tests.

Met One instruments shows that the instrument with the inlet heater (Met One No. 2) read higher than the instrument without the heater (Met One No. 1) by 11 percent (slope = 1.11, R^2 = 0.98).

Discussion—The concentrations measured by the Met One GT-640 did not correlate well with those measured by the Federal Reference Method sampler. This could be due to the small number of data points collected. The 2000 Laboratory tests show the instrument grossly underestimated the mass concentrations by 40 to 50 percent. Although all the real-time continuous instruments underestimated mass concentrations to some degree during the 2000 laboratory tests, the Met One showed the largest discrepancy. Correlation between the two Met One instruments was poor.

2000 Laboratory Tests—Two Met One GT-640's were available for the 2000 laboratory tests. Both underestimated the mass concentrations (figures 14 and 15) when compared to the FRM results. Met One No. 1 had a slope of 0.47 (R^2 = 0.73). Met One No. 2 had a slope of 0.60 (R^2 = 0.78). When the instruments were compared to one another, the No. 2 instrument was reading 26 percent higher than instrument No. 1 (slope = 1.26, R^2 = 0.79).

Results from the high-humidity tests (figures 16 and 17) show both instruments underestimated the mass concentrations. Instrument No. 1 without its inlet heater underestimated mass concentrations by 15 percent (slope = 0.85, R^2 = 0.63). Instrument No. 2 with its inlet heater installed underestimated mass by 6 percent (slope = 0.94, R^2 = 0.61). Comparison of the results of the two

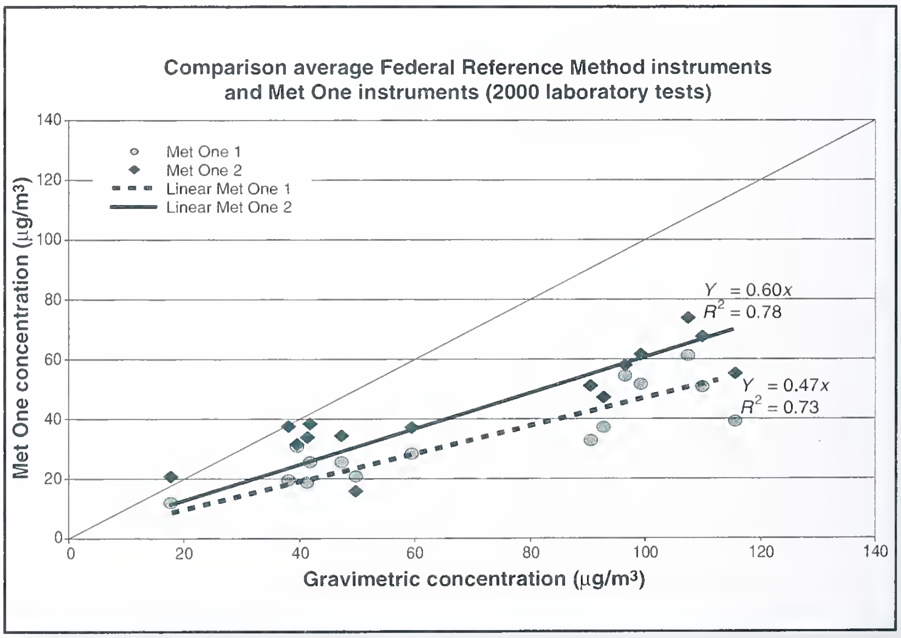

Figure 14—The 2000 laboratory results of the two Met One GT-640's and the gravimetric samplers. Gravimetric results are derived from the average of the two Federal Reference Method samplers.

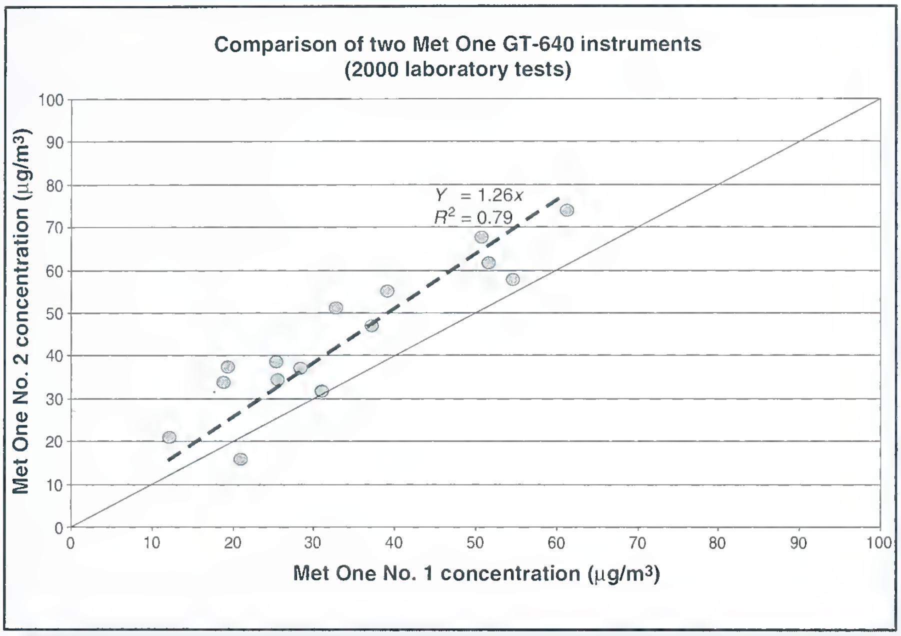

Figure 15—Comparison of the results from the two Met One GT-640 samplers during the 2000 laboratory tests.

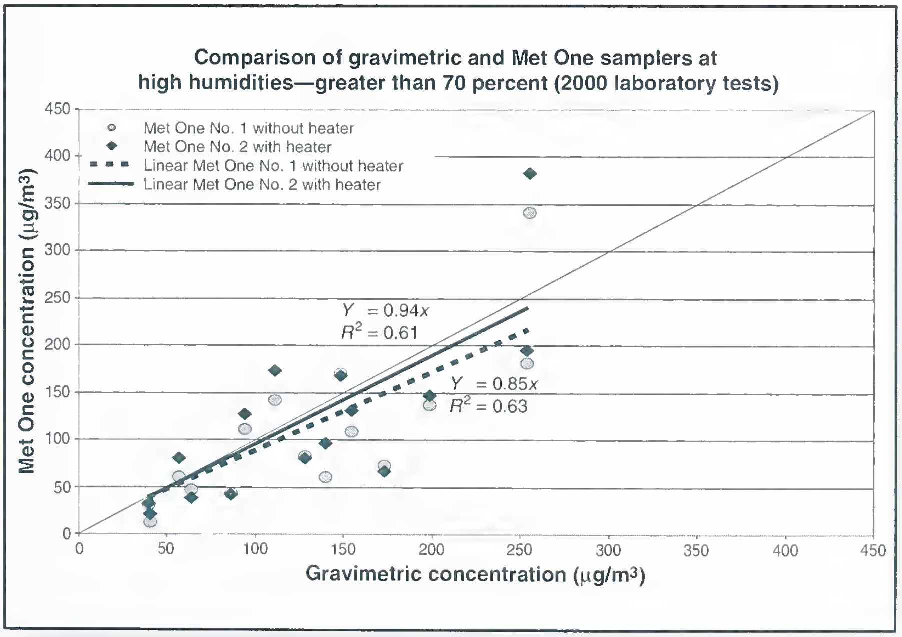

Figure 16—Results of the high-humidity laboratory tests. Instrument No. 1 did not have the inlet heater installed.

One instrument read 26 percent higher than the other. Met One has upgraded the GT-640 to improve the instrument's performance at low particulate concentrations. This may improve the consistency among identical instruments.

The high-humidity tests yielded positive results. In theory, the inlet heater should be drying the particulates as they enter the optical chamber, lowering the mass concentration estimate from the instrument. In this study, even though the instrument with the inlet heater was still reading higher than the one without the inlet heater, the difference between the two decreased (from 26 percent to 11 percent), indicating the heater was removing some moisture from the particulates.

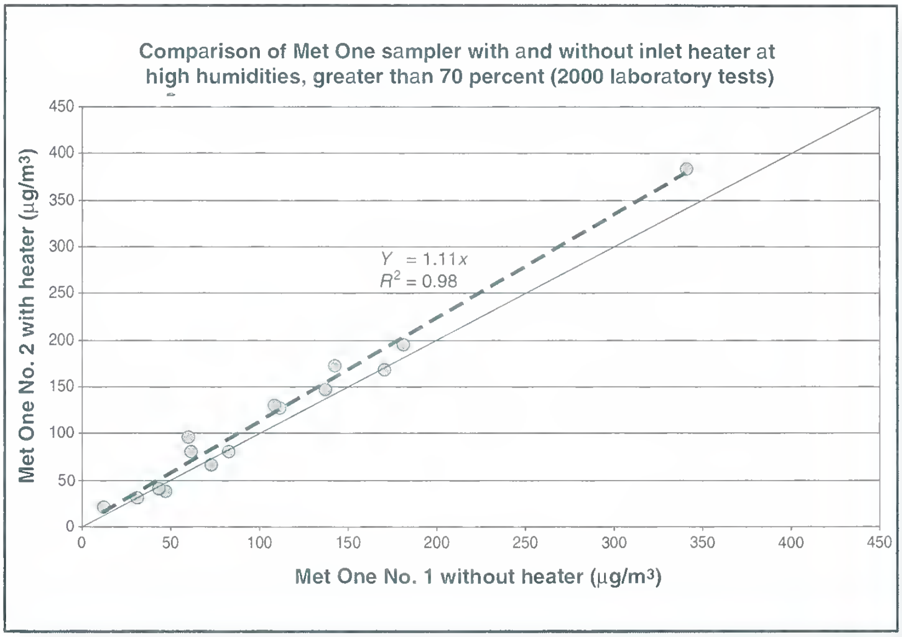

Figure 17—Comparison of the laboratory high-humidity results from two Met One GT-640 instruments.

MIE DataRam

1998 Laboratory Tests—Two DataRams were used for the 1998 laboratory tests. Concentrations measured by the gravimetric sampler during the tests ranged from 20 to 450 $\mu g/m^3$. Figures 18, 19, and 20 show the results. DataRam No. 1 had a slope of 1.93 with an R^2 of 0.98, indicating that it overestimated the mass concentration results from the gravimetric sampler by 93 percent. DataRam No. 2 had a slope of 2.16 with an R^2 of 0.97 when its results were compared to the gravimetric results. Comparison results between the two instruments indicate DataRam No. 2 read 13 percent higher than DataRam No. 1. The slope of the line for the instrument comparison was 1.13 with an R^2 above 0.99, indicating excellent reliability but a need to calibrate each instrument.

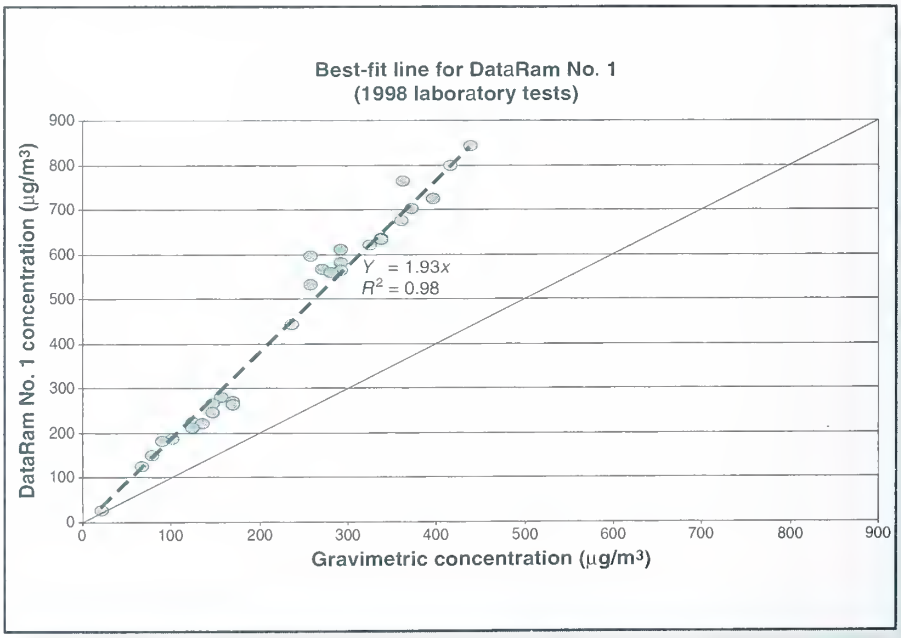

Figure 18—Comparison of the 1998 laboratory results from DataRam No. 1 and the gravimetric sampler. Gravimetric results are from the Fire Sciences Laboratory gravimetric sampler.

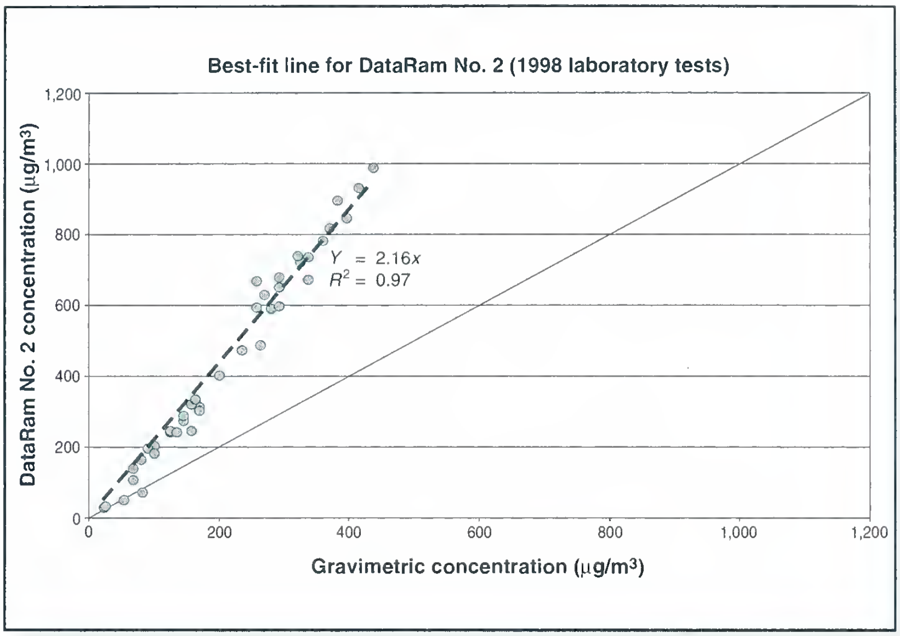

Figure 19—Comparison of the 1998 laboratory results from DataRam No. 1 and the Fire Sciences Laboratory gravimetric sampler.

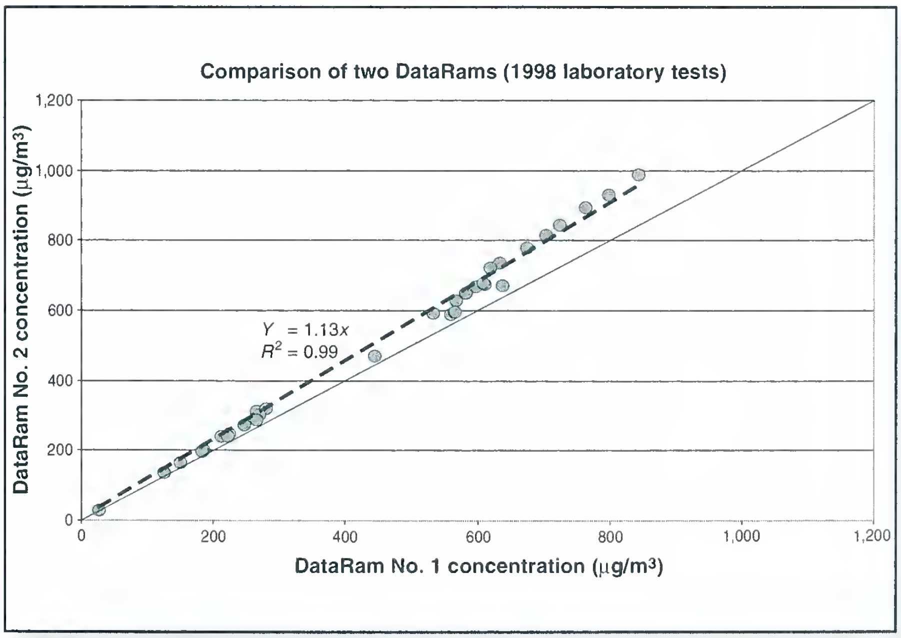

Figure 20—The 1998 laboratory results of the two DataRams plotted against each other.

Field Results—Figure 21 shows the DataRam results for the field collocation study. Field tests conducted in 1998 and 1999 show the DataRam overestimated the gravimetric results by 21 percent (slope = 1.21, R^2 = 0.89, N = 20).

2000 Laboratory Tests—Concentration ranges for the 2000 laboratory tests were intended to be lower than in the 1998 laboratory tests (similar to concentrations that would be seen in actual field use). The concentrations during the 2000 laboratory tests ranged from under 20 $\mu g/m^3$ to just under 120 $\mu g/m^3$ as measured by the FRM. Figure 22 shows the results of the two DataRams compared to results of the average of the two FRM samplers. Both DataRams underestimated the mass concentration. DataRam No. 1 had a slope of 0.70 (R^2 = 0.76) while DataRam No. 2 had a slope of 0.80 (R^2 = 0.79). Comparison of the two DataRams (figure 23) to each other indicates that DataRam No. 2 read 14 percent higher than DataRam No. 1 (slope = 1.14, R^2 = 0.99, N = 15). These instrument comparison results are remarkably similar to the 1998 laboratory results conducted at concentrations more than twice as great, showing instrument consistency and individuality.

High-humidity tests (relative humidity higher than 70 percent) were performed with DataRam No. 1 configured with no inlet heater and DataRam No. 2 with its inlet heater installed. Figures 24 and 25 show the results from those tests. As previously mentioned, at low relative humidities and with the inlet heater installed, DataRam No. 1 had a slope of 0.70 (R^2 = 0.76). At high relative humidities without the inlet heater, the slope increased to 1.38 (R^2 = 0.73). DataRam No. 2 had the inlet heater installed for both the low and high relative humidities tests.

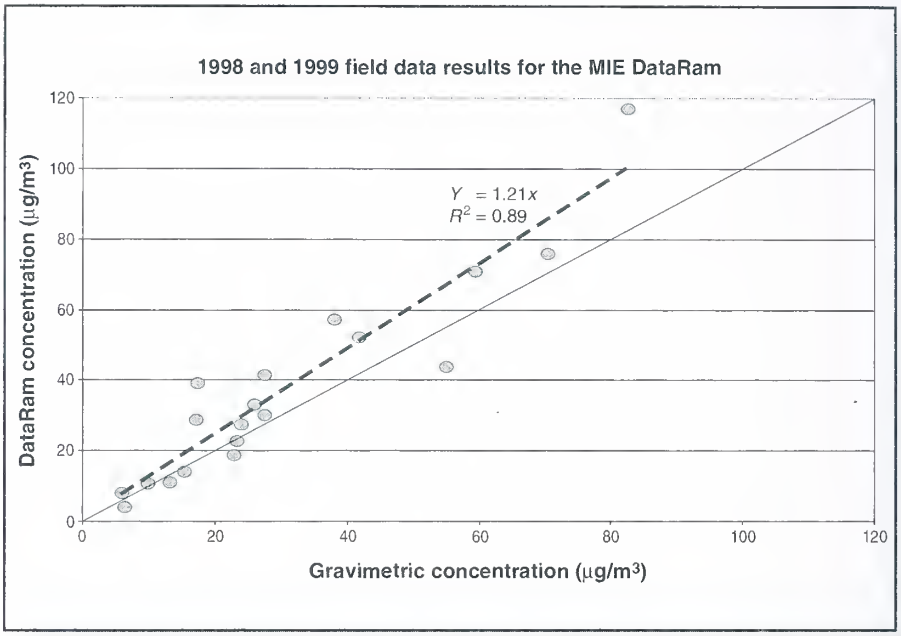

Figure 21—The 1998 and 1999 field results of the DataRam No. 1 plotted against the gravimetric results. Gravimetric results are from the Fire Sciences Laboratory and the Federal Reference Method samplers.

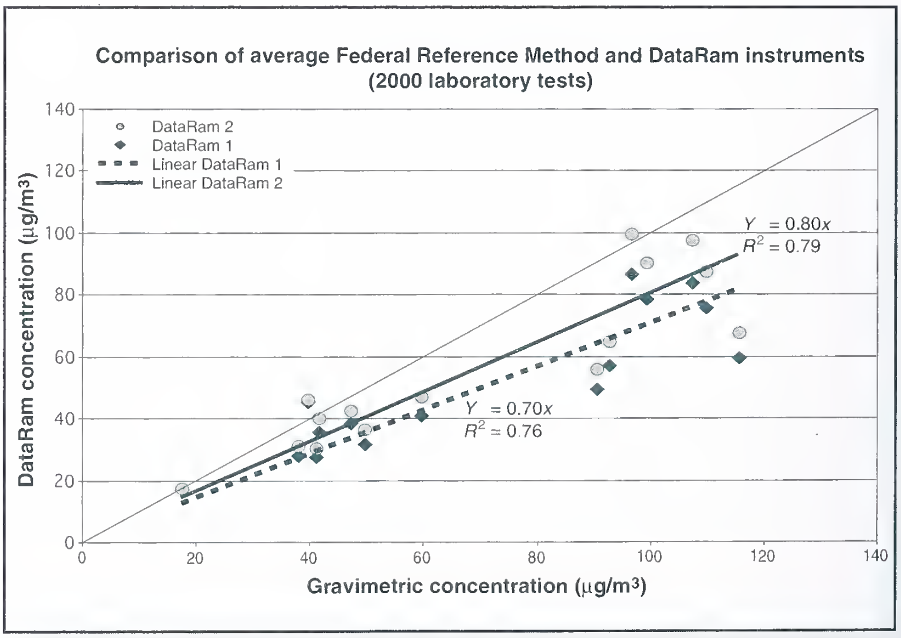

Figure 22—Results of the two DataRams used in the 2000 laboratory tests compared to the gravimetric results. Gravimetric results are derived from the average of the two Federal Reference Method samplers used during the tests.

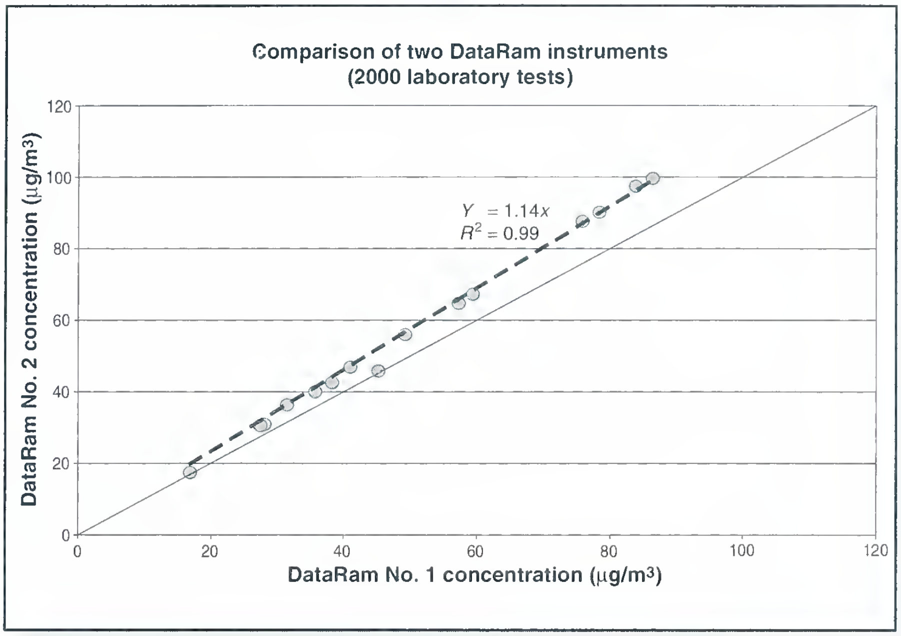

Figure 23—Comparison of the two DataRams used in the 2000 laboratory tests.

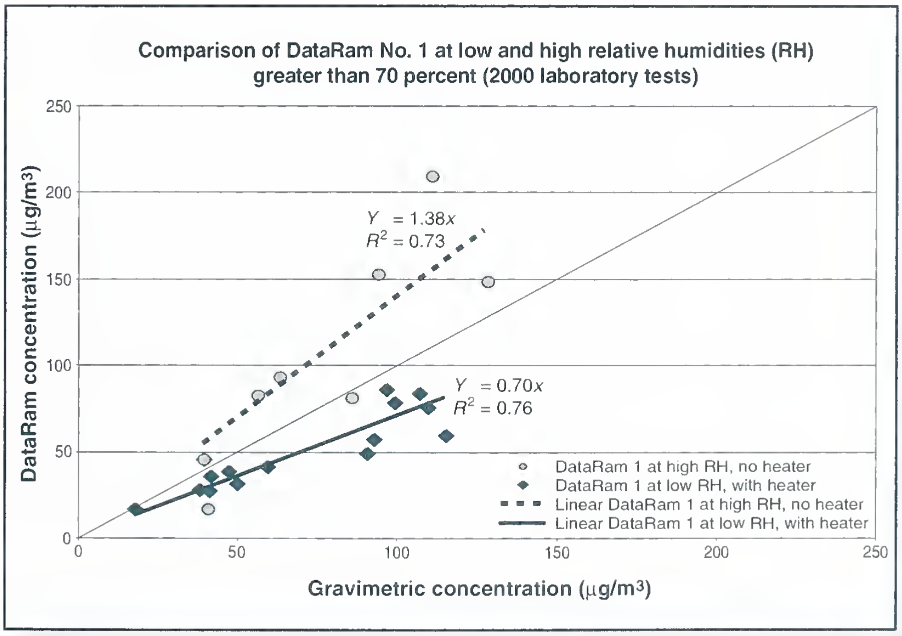

Figure 24—Comparison of DataRam No. 1 at low (less than 40 percent) and high (more than 70 percent) relative humidities during the 2000 laboratory tests. The inlet heater was installed for the low-humidity tests. The inlet heater was removed for the high-humidity tests. Gravimetric results are from the Federal Reference Method sampler.

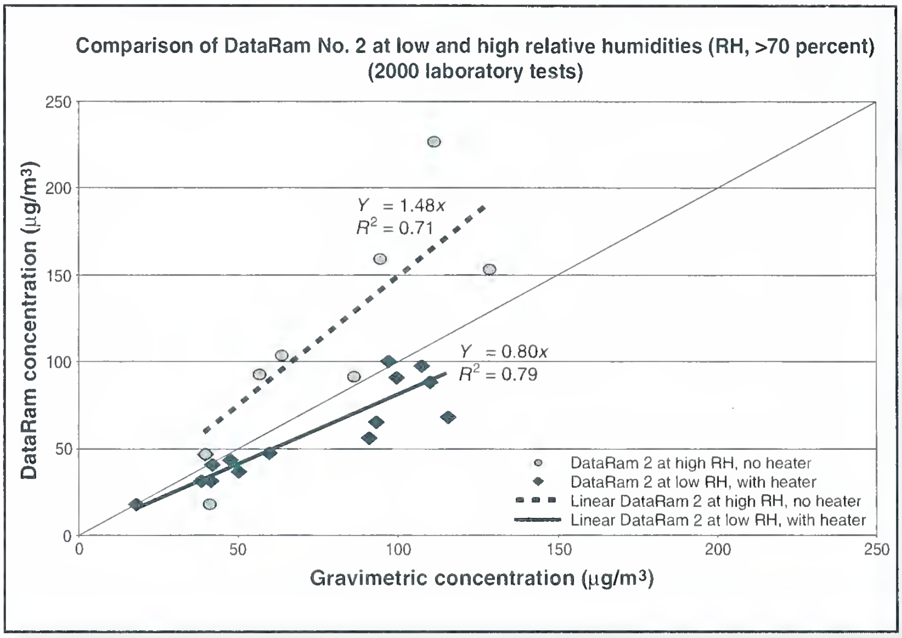

Figure 25—Comparison of DataRam No. 2 at low (less than 40 percent) and high (more than 70 percent) relative humidities during the 2000 laboratory tests. The inlet heater was installed for both the high- and low-humidity tests. Gravimetric results are from the Federal Reference Method sampler.

The slope went from 0.80 (R^2 = 0.79) at low relative humidities to 1.48 (R^2 = 0.71) at high relative humidities.

Discussion—During the 1998 tests when the instruments were exposed to higher particulate concentrations, the DataRam overestimated concentrations by about 93 percent. During the 2000 laboratory tests the DataRam underestimated lower mass concentrations by 20 to 30 percent. Field tests sampling low concentrations (similar to the 2000 laboratory tests) showed that the DataRam overestimated mass concentrations, but not as much as during the high-concentration 1998 laboratory tests. The differences in the laboratory results may be attributed to the different amount of needles being burned. This caused different flaming and smoldering conditions within the fire and may have generated particulates with different optical properties.

The two DataRams compared similarly during previous tests but accuracy was poor. DataRam No. 2 read about 14 percent higher than DataRam No. 1 throughout the tests. The high-humidity tests indicate that the inlet heater is not entirely effective in reducing the moisture content of the particulate. The instruments continue to overestimate mass concentrations. DataRam No. 1's mass concentration estimates increased by 97 percent when relative humidities were above 70 percent and the inlet heater was not installed. DataRam No. 2's mass-concentration estimates increased by 85 percent when relative humidities were above 70 percent, even when the inlet heater was installed.

Radiance Research Nephelometer

1998 Laboratory Tests—The Radiance Research nephelometers overestimated the mass-concentration results by 1.90 for sampler No. 1 and 1.81 times for sampler No. 2 (figures 26 and 27). The R^2 values were 0.97 and 0.92, respectively. For the 12 samples when two Radiance nephelometers were collocated, Radiance No. 2 underestimated the mass-concentration estimate of Radiance No. 1 by 5.5-percent (slope = 0.95, R^2 = 0.99). Concentration ranges for the tests varied between 20 μg/m^3 and 450 μg/m^3 as measured by the gravimetric sampler.

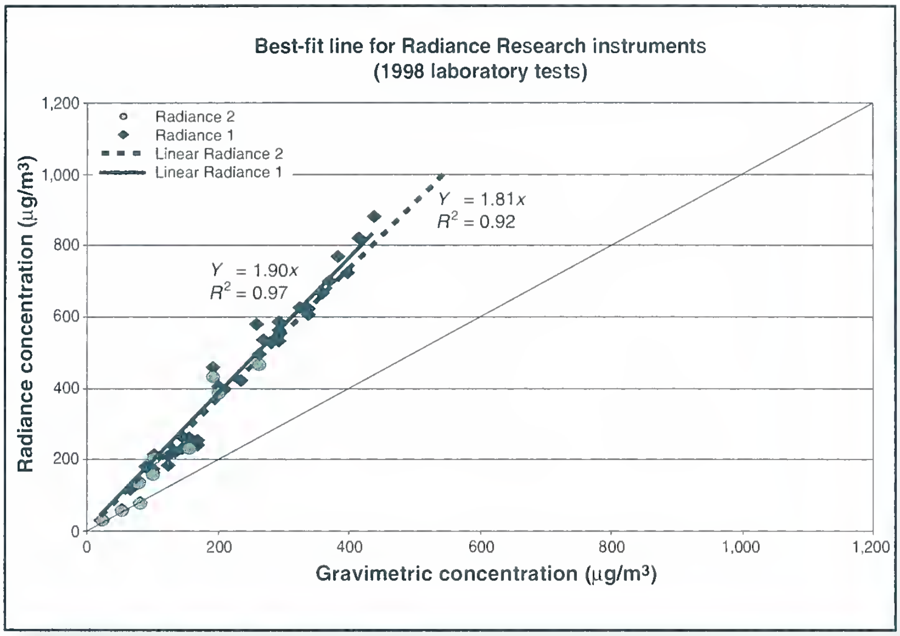

Figure 26—The 1998 laboratory results of the two Radiance Research nephelometers and the gravimetric sampler. Gravimetric results are from the Fire Science Laboratory gravimetric sampler.

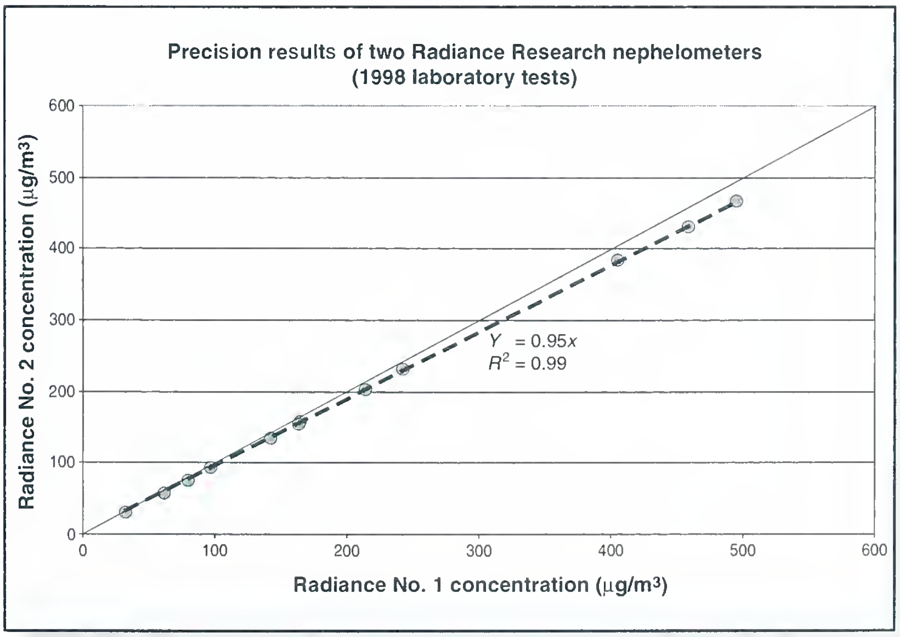

Figure 27—The 1998 laboratory results of the two Radiance Research nephelometers compared to one another.

Field Tests—Results from the field tests (figures 28 and 29) show both the Radiance Research nephelometers overestimated the mass concentration results of the FRM samples. Radiance No. 1 overestimated the concentrations by 27 percent (slope = 1.27, R^2 = 0.78, N = 22). Radiance No. 2 overestimated the concentrations by 57 percent (slope = 1.57, R^2 = 0.90, N = 14). Radiance No. 2 was not used for all the field tests. For this reason, different slopes were obtained for the two nephelometers. Comparing the results when both of the Radiance nephelometers were available shows that they estimate essentially the same mass concentration for the field tests (slope = 1.00, R^2 = 0.97, N = 14).

2000 Laboratory Tests—The 2000 laboratory test results (figures 30 and 31) show that both Radiance Research nephelometers overestimated mass concentrations when compared to the average results of the two FRM's. Radiance No. 1 overestimated concentrations by 12 percent (slope = 1.12, R^2 = 0.90, N = 13) while Radiance No. 2 overestimated the concentrations by 14 percent (slope = 1.14, R^2 = 0.90, N = 14). The Radiance nephelometers estimated total suspended particulate while the other instruments estimated $PM_{2.5}$ and smaller.

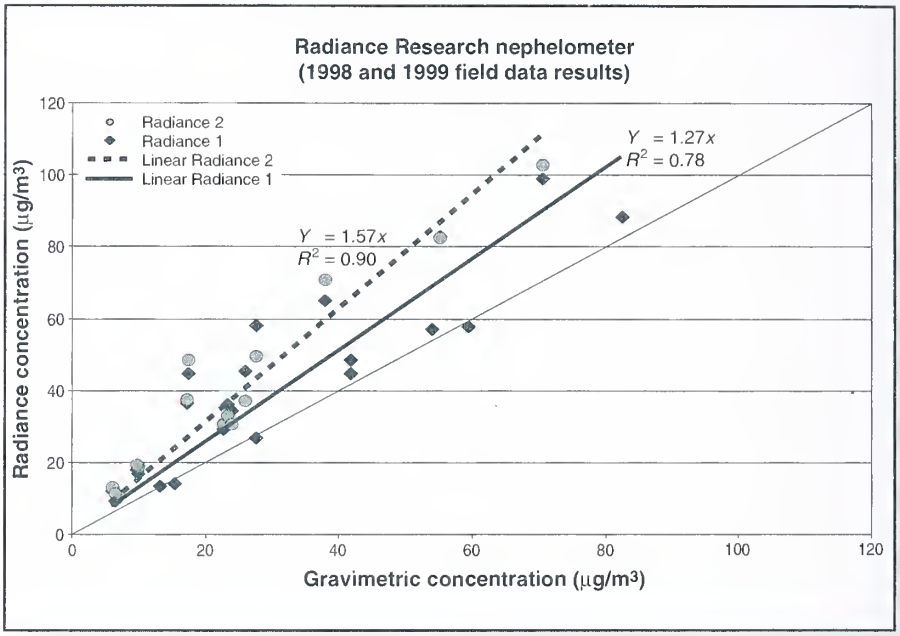

Figure 28—The 1998 and 1999 field results of the two Radiance Research nephelometers and the gravimetric samplers. Gravimetric results are from both the Fire Sciences Laboratory and Federal Reference Method samplers.

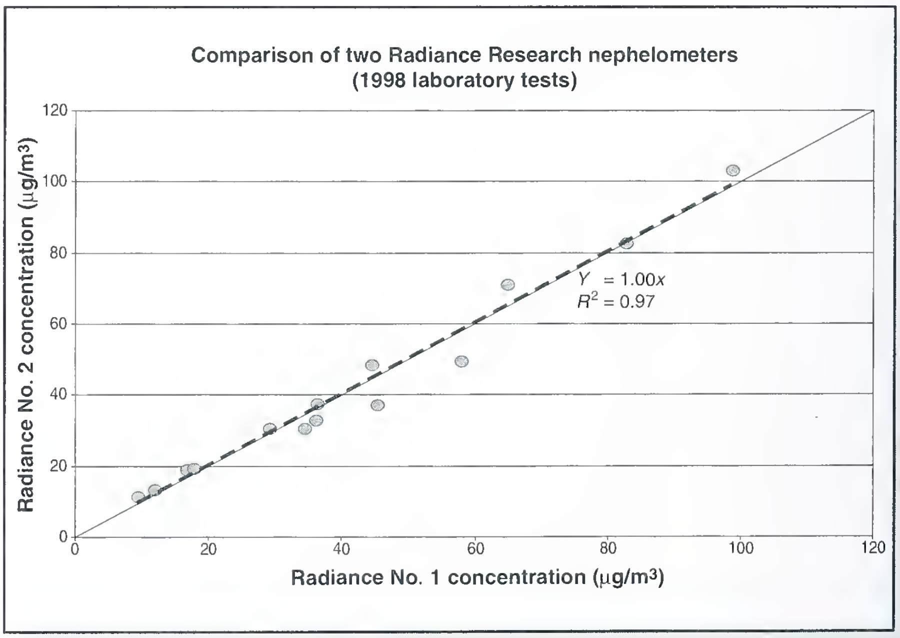

Figure 29—Comparison of the two Radiance Research nephelometers used in the field tests.

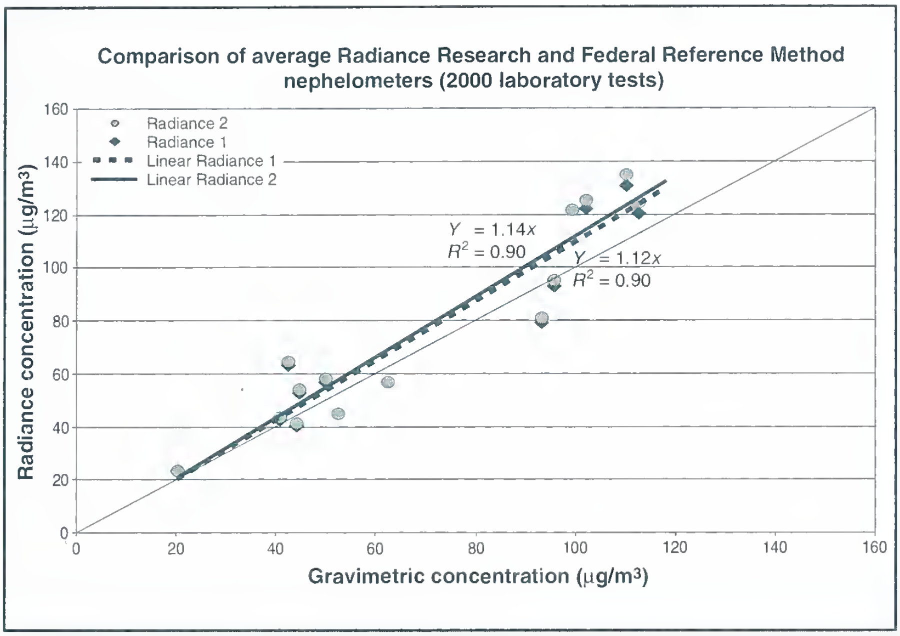

Figure 30—The 2000 laboratory results of the two Radiance Research nephelometers compared to the average result from the Federal Reference Method gravimetric samplers used in the tests.

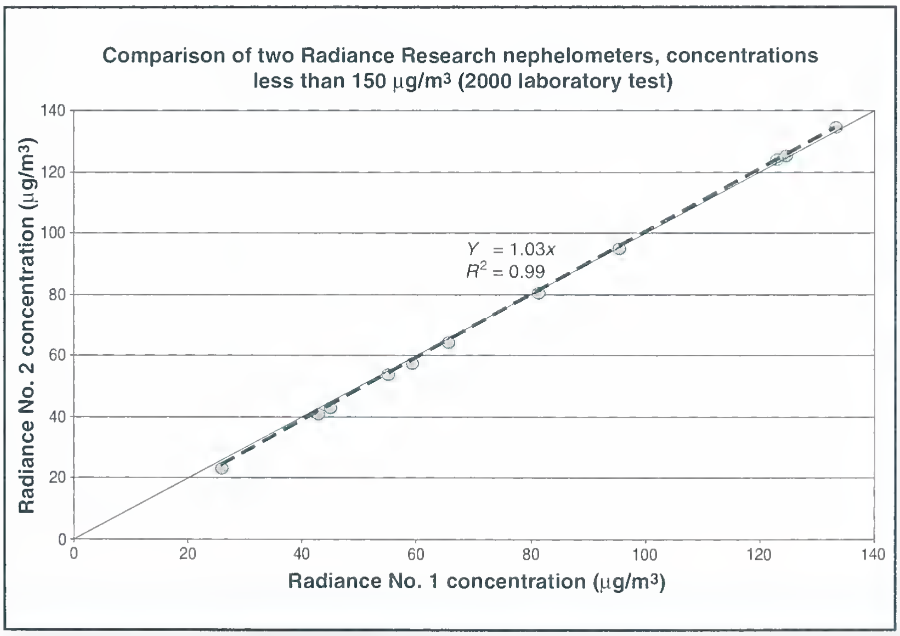

Figure 31—Comparison of the results from the two Radiance Research nephelometers in the 2000 laboratory tests.

At high humidities (higher than 70 percent), the Radiance nephelometers overestimated the mass concentrations by 51 percent (with inlet heater) and 64 percent (without inlet heater, figures 32 and 33). The Radiance nephelometer with the inlet heater had a slope of 1.51 and an R^2 value of 0.87. The nephelometer without the inlet heater had a slope of 1.65 and an R^2 value of 0.84. The Radiance nephelometer with the inlet heater read 9 percent lower than the nephelometer without the heater (slope = 0.91, R^2 = 0.98, N = 14).

Discussion—The Radiance Research nephelometer performed much like the DataRam. It overestimated mass concentrations by 80 to 90 percent during the 1998 laboratory tests. The overestimate was 10 percent during the 2000 laboratory tests. The field test overestimates were between the 1998 and 2000 laboratory overestimates. The difference in the laboratory results may be attributable to differences in the amount of needles burned during the tests.

The Radiance nephelometers showed excellent consistency when compared against each other. The instruments consistently read within 5 percent of each other with very high correlations.

The high-humidity tests indicated that the inlet heater does affect the mass concentration estimations. The nephelometer with the inlet heater had readings 9 percent lower than the one without.

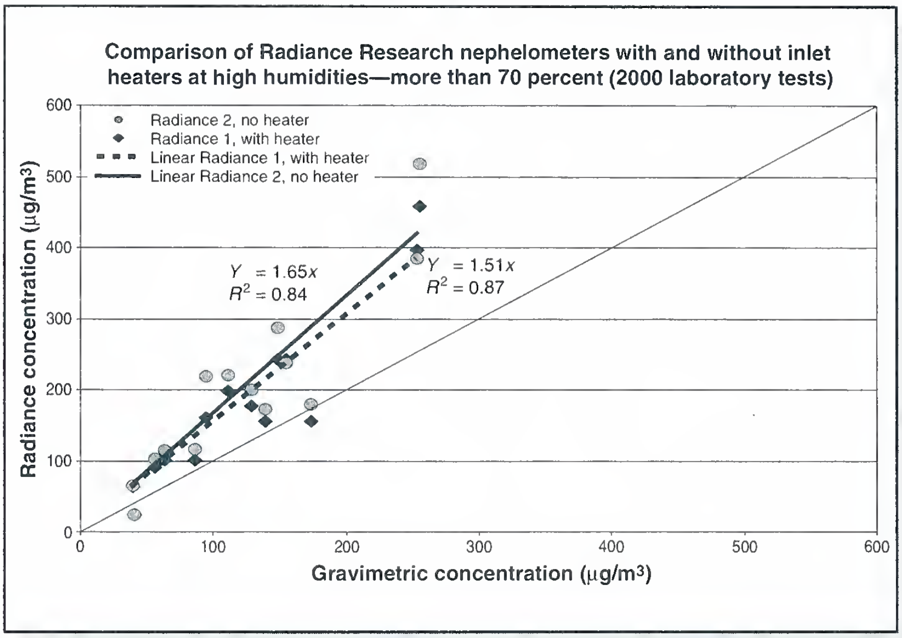

Figure 32—Comparison of the results from the Radiance Research nephelometers and the gravimetric sampler. Radiance No. 1 had an inlet heater while Radiance No. 2 did not. Gravimetric results are from the Federal Reference Method sampler.

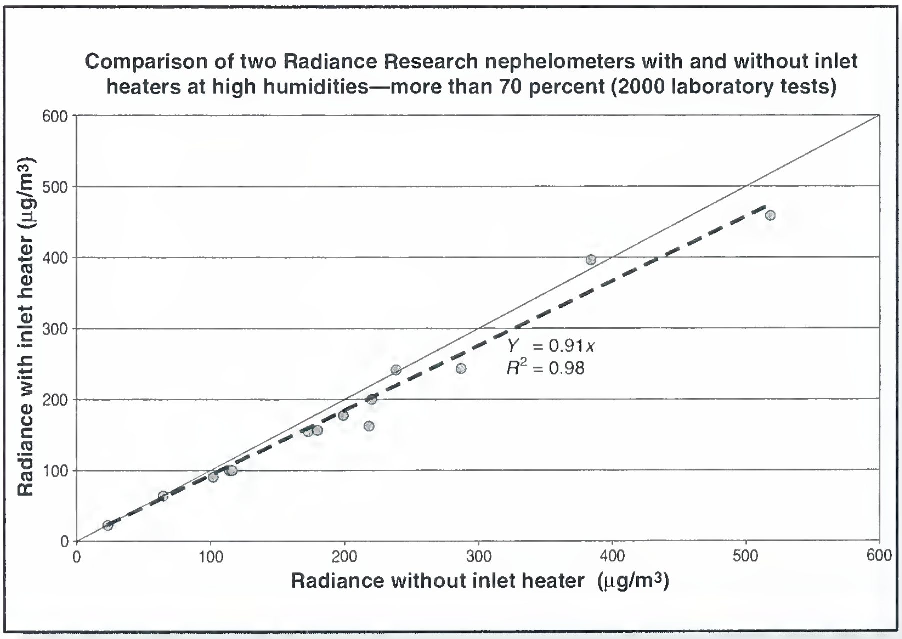

Figure 33—Comparison of the two Radiance Research nephelometers used during the high-humidity tests.

Optec NGN-3 Nephelometer

The Optec NGN-3 was not available for the 1998 laboratory or field tests.

2000 Laboratory Tests—The Optec NGN-3 underestimated the mass concentrations by 33 percent (slope = 0.68, R^2 = 0.81, N = 14) when compared to the average results from the two FRM samplers (figure 34). The results for the tests were presented using a conversion factor of 3.0 from B*scat* to mass concentration, the factory preset value. At high humidities, the NGN-3 with the correction factor set at 3.0 underestimated the mass concentrations by 6 percent (slope = 0.94, R^2 = 0.84, figure 35).

Discussion—The Optec NGN-3 is a new instrument and was not available for all the tests. The 2000 laboratory results were consistent with the other real-time continuous instruments. No instrument comparison results are available because only one instrument was included in the study.

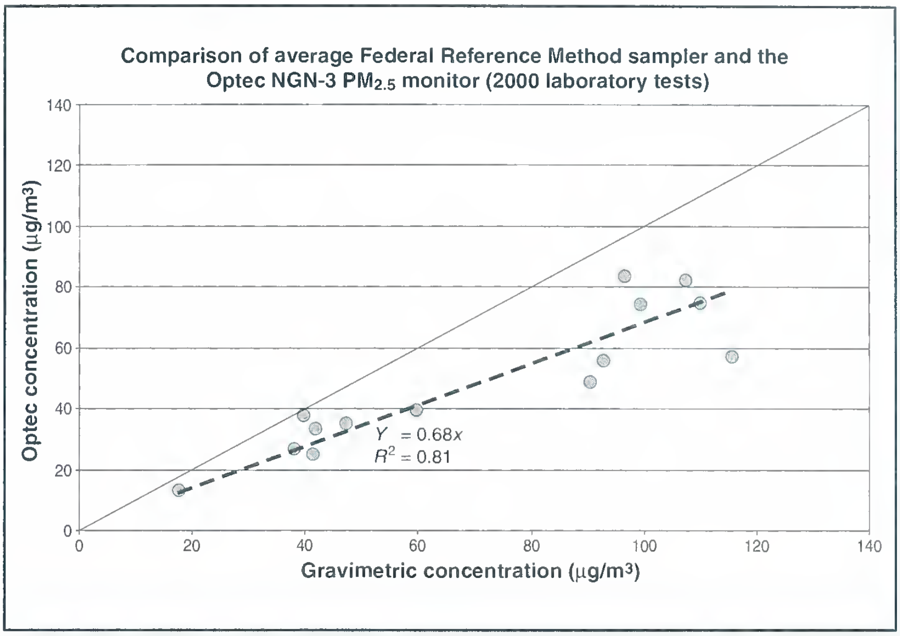

Figure 34—The 2000 laboratory results of the Optec NGN-3 nephelometer and the average of the two Federal Reference Method gravimetric samplers.

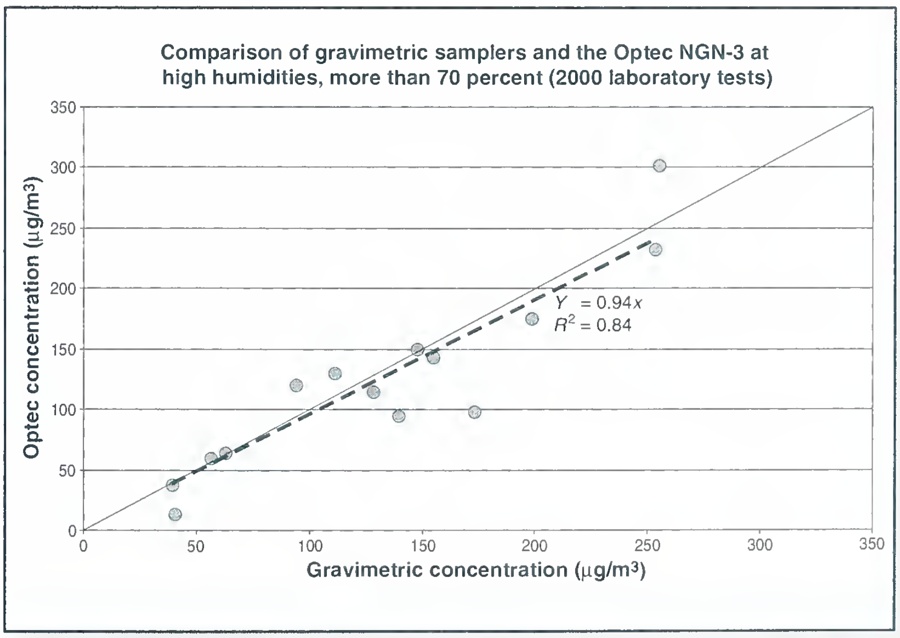

Figure 35—Results of the high-humidity tests for the Optec NGN-3 nephelometer compared to the gravimetric results. Gravimetric results are from a Federal Reference Method sampler.

Andersen Aethalometer

The aethalometer was not available for the 1998 laboratory tests and was available only for part of the field tests. No data are available for the 2000 lab tests because of a configuration problem with a $PM_{2.5}$ cutoff inlet. The problem was found after testing was complete, voiding the test results.

Field Tests—For the few field tests in which the Andersen aethalometer was used, it overestimated the mass concentration. Figure 36 shows the best-fit line with a slope of 11.99, an intercept of 90 $\mu g/m^3$, and an R^2 value of 0.92.

Discussion—Results for the Andersen aethalometer are very limited and should be considered preliminary.

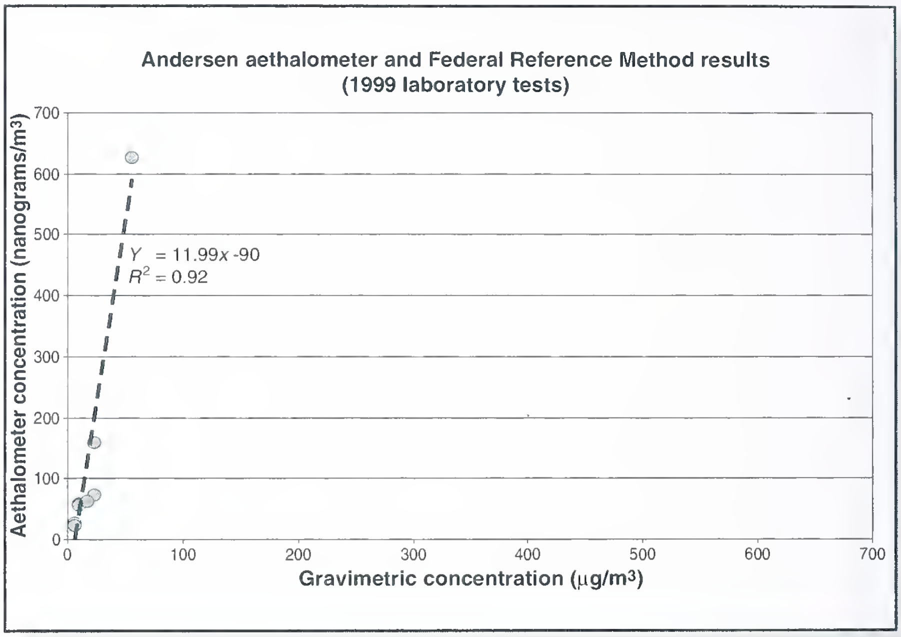

Figure 36—The 1999 laboratory results of the Andersen aethalometer compared to the results of a Federal Reference Method sampler.

Summary

We surveyed commercial off-the-shelf instruments that would meet the Forest Service's needs for real-time continuous smoke sampling at a reasonable cost in remote locations. Our survey originally included gravimetric and optical devices. We narrowed our evaluation to optical devices because they can provide smoke or air quality managers with continuous, real-time estimates of particle concentrations.

Optical instruments use light absorption, forward-scattering, or backscattering to infer the presence of particles. Based on the size, shape, and refractive index of the particles, a series of equations relates the amount of light scattered or absorbed to the particulate concentration. Aerosols having a consistent size and shape distribution can be estimated fairly accurately with these equations. However, smoke particles have a wide variety of sizes and shapes and their physical characteristics are dependent on the fuel characteristics and on whether the particles were formed during flaming or smoldering combustion. Once in the atmosphere, the particles continue to change with temperature, moisture content of the air, sunlight exposure, and other factors. The greatest amount of change occurs immediately after combustion, but the process continues for days at a reduced rate. Because of this variability in the size and shape of the smoke particles, it is difficult using current optical techniques to define a highly accurate equation for determining particulate matter concentrations. Another difficulty is that aerosols have different light-scattering and absorption responses, depending on the orientation of the light receiver to the particles and to the light source. The response from a forward-scattering device may differ from that of a backscattering device. We did not evaluate whether the algorithms selected by the instrument vendors were appropriate for a particular biomass smoke event or not.

Our standard measure during most of the field tests and during the 2000 test was provided by two Federal Reference Method monitors, the Partisol Model 2000 and the BGI PQ200. The FRM monitor is gravimetric and has been selected by the U.S. Environmental Protection Agency as the approved method for measuring fine particles (2.5 µm and smaller). For the purpose of this study, the two monitors compared well against each other, showing less than 3-percent variability. A gravimetric device built and used by Forest Service research for aerial particle sampling was used as the standard for the 1998 high concentration evaluation. On average, it reported concentrations about 10 percent lower than the FRM.

The five brands of optical instruments we evaluated were similar in many ways. All of them were more or less portable for one person and rugged enough to withstand frequent relocation in the field. All but the aethalometer were battery powered. Each instrument was reasonably easy to operate and acceptably reliable. The brands for which we had two identical instruments showed good measurement consistency between instruments. In other words, there were few fundamental discriminating characteristics other than accuracy that showed one or more instruments to be clearly superior to the others. Our summary of some instrument features (table 2) and our subjective rating of characteristics other than accuracy may help users choose one instrument over another for a particular application (table 3).

Conclusions

The instruments had substantial differences in their measurement performance. Our data were collected in four distinct experiments, two in a smoke chamber, where a handful of pine needles were burned in a flaming and smoldering state, and two in ambient conditions near open forest fires. One indoor test and the two outdoor tests were conducted when the particle concentrations in the vicinity of the samplers were relatively low (less than about 150 $\mu g/m^3$). In the other indoor experiment, concentrations reached almost 500 $\mu g/m^3$. Some of the low-concentration indoor tests were conducted while the relative humidity (RH) was raised above 70 percent. The high-humidity tests were intended to evaluate two aspects of particle sampling; one was to show the relative difference in concentration using optical devices when the humidity was high and when it was low; the other was to compare the response of identical instruments when they were tested with and without a heater.

When the instruments were tested in a smoke chamber and exposed to moderately high particle concentrations (similar to those experienced by firefighters) their approximate performance was:

- MET One GT-640—Unavailable.
- MIE DataRam—Overestimated by about 93 percent.
- Radiance Research—Overestimated by about 85 percent.
- Optec NGN-3—Unavailable.
- Andersen aethalometer—Unavailable.

At lower particle concentrations (closer to the ambient air-quality standards and at levels where visibility is noticeably impaired) the instruments' approximate performance was:

- MET One GT-640—Underestimated by about 53 percent.
- MIE DataRam—Underestimated by about 25 percent.
- Radiance Research—Overestimated by about 13 percent.
- Optec NGN-3—Underestimated by 10 to 32 percent.
- Andersen aethalometer—Unavailable.

During field tests when particle concentrations were close to the ambient air-quality standards and at levels where visibility is noticeably impaired, the instruments' approximate performance was:

- MET One GT-640—Overestimated by about 10 percent, but data were scattered.
- MIE DataRam—Overestimated by about 21 percent.
- Radiance Research—Overestimated by about 42 percent, but substantial difference in the two instruments.
- Optec NGN-3—Unavailable.
- Andersen aethalometer—Insufficient data.

During laboratory tests when the concentrations ranged to 350 $\mu g/m^3$ and the humidity was above 70 percent, the approximate performance was:

- MET One GT-640
  Heater: Underestimated by 6 percent.
  No Heater: Underestimated by 15 percent with some data scatter.

- MIE DataRam
  Heater: Overestimated by 40 percent.
  No Heater: Overestimated by 30 percent.

- Radiance Research
  Heater: Overestimated by 51 percent.
  No Heater: Overestimated by 65 percent.

- Optec NGN-3
  Heater: Underestimated by 5 percent.
  No Heater: Unavailable.

- Andersen aethalometer
  Heater: Unavailable.
  No Heater: Unavailable.

These optical instruments are not suited for evaluating whether particles in the air are from biomass smoke or some other source; nor are they intended to ascertain whether ambient air-quality standards are being met. The best use for these instruments is to determine whether the local aerosol concentration is relatively high or low and whether concentrations are going up or down. For these purposes, each of the instruments has some capability.

Recommendations

Accurately estimating ambient particle concentrations from their light-scattering and absorption properties is a difficult proposition. Accuracy could be improved by calibrating the instruments for a type of fire event and accounting for meteorological conditions and the existing levels of ambient particles. Conditions to consider include the:

- Age of the smoke.
- Type of fire, whether flaming or smoldering.
- Fuel moisture.
- Relative humidity.
- Background particle concentration without smoke from the fire.

Monitoring estimates also could be compared to the estimates from a good real-time smoke model.

Appendix—Instrument Specifications

RTAA 800 Real-Time Aethalometer	**Andersen Instruments, Inc.** 500 Technology Ct. Smyrna, GA 30082 Home Page: http://www.Andersеninstruments.com
Flow rate	2 to 6 L/min, user adjustable 0- to 10-L/min mass flow meter standard.
Analysis time base	2 s to 1 h.
Pump	Internal diaphragm pump.
Optoelectronics	Analysis at 880 nm, 22-bit A/D.
Display	Four-line LCD panel with keyboard and status indicator lamps.
Processor	Embedded 386-class computer, program and operating parameters stored in EPROM.
Size and weight	10.5 x 12.5 in (rack mount), 20 lb.
Power requirements	110 V, 69 Hz, 100 W.
Data output	3.5-in floppy disk, RS-232, analog outputs.
Filtration medium	15-m roll of quartz fiber tape.

PQ200A Air Sampler

BGI, Inc.
PQ200A Air Sampler
58 Guinan St.
Waltham, MA 02451
Home Page: http://www.bgiusa.com

Filter .... 2 μm, 47-mm Teflon.

Flow rate .... 16.7 L/min.

EPA designed-specified hardware .... EPA omnidirectional ambient particle inlet.
Inlet sample transport tube.
EPA $PM_{2.5}$ Well Impactor Ninety-Six (WINS).
47-mm filter holder assembly, 47-mm Teflon.

Size and weight
- Enclosure .... 48 lb.
- Without battery .... 40 lb.
- Dimensions .... 16 x 19 x 18 in.
- Height of inlet aboveground .... 6.57 ft.

EPA performance-specified and PQ200 featured hardware
- Ambient temperature sensor range .... -30 to +50 °C ±0.16 °C.
- Ambient barometric pressure sensor.
- Volumetric flow control and measurement system.
- Microprocessor.
- RS-232 communication.

GT-640 Logger Particulate Monitor

Met One Instruments
1600 Washington Blvd.
Grants Pass, OR 97526
Home Page: http://www.metone.com

Range .... 0 to 10,000 $\mu g/m^3$.

Sensitivity .... 1 μg.

Accuracy (1 min) .... 2-percent concentration 0.000 to 1.000 mg.

Accuracy (1 h) .... 1-percent concentration 0.000 to 1.000 mg.

Particulate data period .... 1-min standard (1- to 60-min option).

Logger sample .... Once per second.

Logger data period .... Selectable 1, 5, 15, 60 min.

Flow rate .... Up to 5 L/min (depending on inlet).

Power .... 12 V dc, 1 A (including inlet heater) from external battery or using No. 3813 universal power supply. (No. 3813 supply accepts 90 to 264 V ac, 47- to 63-Hz power sources).

Operating temperature range ..... 0 to 50 °C with internal heater, 0- to 100-percent relative humidity with inlet heater.

Outputs .... RS-232 for modem, radio, or direct connection to PC.

Alarm channels (optional) .... Two with relay contacts (normally open) (maximum power 24 V dc at 20 mA).

Analog output (optional) .... 0 to 1 V analog, 0 to 1 mg/m^3.

Data storage .... 210 days at 1-h data period.

DataRam

MIE, Inc.
7 Oak Park
Bedford, MA 01730
Home Page: http://www.mieinc.com

Concentration measurement ranges	0.1 to 999.9 $\mu g/m^3$ (resolution: 0.1 $\mu g/m^3$). 1.0 to 39.99 mg/m^3 (resolution: 0.01 mg/m^3). 40.00 to 399.9 mg/m^3 (resolution: 0.1 mg/m^3).
Wave length	880 nm.
Scattering coefficient ranges	1.5×10^{-7} to 6×10^{-1} m^{-1}.
Concentration display averaging/updating time	1 to 10 s.
Instrument comparison/repeatability	±0.3 $\mu g/m^3$ for 10-s average, ±1.0 $\mu g/m^3$ for 1-s average.
Accuracy	±5 percent of reading ± precision.
Temperature coefficient of zero level	Less than 0.05 $\mu g/m^3$ per degree Celsius.
Particle size range of maximum response	0.1 to 10 μm.
Sampling flow rate	1.7 to 2.3 L/min.
Data logging averaging periods	1 s to 4 h.
Total Number of data points in memory	20,000 (each point: average, minimum, and maximum concentrations).
Real time and date data	Seconds, minute, hours, day of month, month and year, with leap year compensation.
Clock accuracy	±1 min/month or better.
Digital output	RS-232, 9,600 baud, 8 data bits, 1 stop bit, no parity bits.
Operating environment	0 to 40 °C (32 to 104 °F), 0 to 95 percent relative humidity.
Dimensions	134 (5.28) x 184 (7.25) x 346 (13.63) mm (in) (H x W x D).
Weight	5.3 kg (11.7 lb).

NGN-3 Open-Air Integrating Nephelometer

Optec, Inc.
Open-Air Integrating Nephelometer
199 Smith St.
Lowell, MA 49331
Home Page: http://www.optecinc.com

Extinction range	0 to 32,768 count (serial output); 0 to 10 V (analog channel 1 or 2).
Resolution	±1 count (serial output; one Rayleigh is equal to 12 counts).
	±2.44 mV (analog channel 1 or 2; one Rayleigh is equal to 12 mV).
Accuracy	±10 percent of true value for air near Rayleigh and using 2 min of integration.
Measured wavelength	550 nm center wavelength, 100-nm bandwidth (photopic response)
Output, serial	RS-232, RX, TX, GND; 8 data bits, 1 stop bit, no parity. Televideo 920 emulation, full-duplex mode 9,600-baud default, others selectable.
Output data, serial	Status, raw scattered light count, raw lamp brightness count, normalized scattered light count, integration time in minutes, temperature, date (year:month:day), time (hour:minute).
Output data, analog	Channel 1, normalized scattered light.
Output data, analog	Channel 2, status value.
Power supply	13.8 ±0.3 V dc, 4.5 A, regulator required.
Operating temperature	-20 to 45 °C.
Size	10.7 x 8.2 x 16.5 in.
Weight	27 lb.
Meteorological sensors temperature	±0.5 °C from -30 to +70 °C.
Humidity	±2 percent relative humidity from 0- to 100-percent relative humidity at 25 °C.

M903 Nephelometer (ROM version 2.37)

Radiance Research
535 NW. 163 St.
Seattle, WA 98177

Principle parameter	Light-scattering extinction coefficient, integrating nephelometer.
Range	0 to 1 km^{-1}.
Lower detection	Less than 0.001 km^{-1} at 30-s average.
Outputs	Four analog (0- to 5-V dc) and RS-232 serial, baud rate selectable, 9,600, 4,800, 2,400, 1,200.
Time constant	Adjustable: 2 to several minutes.
Electronics	Computer-based, MD68HC11 at 8 MHz operating parameters, diagnostics through serial port, three sets of default operating parameters selected with panel switches.
Optics	No lenses. Reference brightness measurement and chopper-stabilized span. Chopper rate adjustable (typically, 20-percent duty cycle).
Wavelength	530 nm.
Sample volume	0.44 m^3.
Weight	About 2.6 kg (6 lb) depending on application configuration.
Size	56 x 13 x 17 cm (L x W x D).
Operating voltage	12 V dc (0.8 or 1 A supplied).
Power usage	2.5 to 3 W (230 mA at 12 V dc) without fan at maximum flash rate; less power at lower flash rates. The supplied fan is 0.8 W.
Selected averaging periods	20 s to 1 h.
Internal data storage	Diagnostic parameters, zero and span settings and time stored in RAM.
Internal clock	Two weeks of 5-min averages can be stored.

Inhouse Filter System	**USDA FS, Rocky Mountain Research Station** Fire Chemistry Group P.O. Box 8089 Missoula, MT 59807 Phone: 406–329–4866
Flow rate	28 L/min.
Filter medium	37-mm Teflon filter.

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Mary Ann Davies is a Project Leader working for the Facilities, Recreation, Fire, and Watershed, Soil, and Air Programs. She received a bachelor's degree in mechanical engineering with a minor in industrial and management engineering from Montana State University in 1988. Her Forest Service career began in the Pacific Northwest Region where she worked with facilities, tramways, fire, and recreation. Mary Ann worked for the Rocky Mountain Research Station's Fire Sciences Laboratory in Missoula before coming to MTDC in 1998.

Rich Fisher has bachelor's degrees in life science (U.S. Air Force Academy) and in meteorology (North Carolina State University). He has master's degrees in earth science (Colorado State University) and in international and strategic studies (Naval War College). He is a certified consulting meteorologist and is Reserve Assistant to the Director of Weather for the Air Force in the Pentagon.

Harold Thistle received a Ph.D. in plant science specializing in forest meteorology from the University of Connecticut in 1988. He is certified by the American Meteorological Society as a Certified Consulting Meteorologist (CCM) and was a consultant in private industry before joining MTDC in 1992. He served as the Center's Program Leader for Forest Health Protection until 1998, developing modeling techniques that accurately describe transport of pesticides in the atmospheric surface layer and evaluating meteorological instrument systems for environmental monitoring. Harold now works with the Forest Health Technology Enterprise Team in Morgantown, WV.

Ronald Babbitt has bachelor's degrees in forestry and electrical engineering. He joined the Forest Service in 1975 and has worked in areas of forest utilization, forest engineering, and fire research. He now works with the Fire Chemistry Research Project at the Fire Sciences Laboratory in Missoula, MT.

Library Card

Trent, Andy; Davies, Mary Ann; Fisher, Rich; Thistle, Harold; Babbitt, Ronald. 2000. Evaluation of optical instruments for real-time, continuous monitoring of smoke particulates. Tech. Rep. 0025-2860-MTDC. Missoula, MT: U.S. Department of Agriculture, Forest Service, Missoula Technology and Development Center. 38 p.

Evaluates five commercially available optical instruments to measure particulate for forest fire smoke in real time. The instruments include the Met One GT-640, MIE DataRam, Radiance Research Nephelometer Model M903, Optec NGN-3 $PM_{2.5}$ Size-Cut Nephelometer, and the Andersen RTAA 800 Aethalometer. Airborne particulates, especially those particles smaller than 2.5 μm in diameter ($PM_{2.5}$), pose potential health, visibility, safety and nuisance problems. Measuring airborne particulate concentrations is very important to land managers as the use of managed forest and rangeland burning increases. The key items of the evaluation were accuracy in measuring or estimating smoke concentrations, comparing results from identical instruments, reliability, cost, and operational characteristics such as portability, power requirements, and data collection. The data were from lab and field settings.

The five brands of optical instruments had few fundamental differences. Accurately estimating ambient particle concentrations from light-scattering and absorption properties is difficult. However, optical instruments can estimate the direction of change and magnitude of the overall ambient particulate concentration, providing useful information to air-quality specialists and land managers.

Keywords: aethalometers, air quality, gravimetric samplers, nephelometers, real time, samplers, smoke management, wood smoke

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